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This report presents a consolidation of existing data on various devices used to suppress vortex-induced motions of cables and circular cylinders in the ocean. The types of devices discussed herein include "fringe," "hair," and ribbon flexible fairings and helical ridges. In general, the available data show that all of these methods do, in fact, suppress vortex-induced vibrations to a greater or lesser degree. However, because of the diverse ways in which suppression effectiveness has been measured, comparisons among different types of devices are difficult to make. Criteria for such comparisons are suggested. Relatively few

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This report presents a consolidation of existing data on various devices used to suppress vortex-induced motions of cables and circular cylinders in the ocean. The types of devices discussed herein include "fringe," "hair," and ribbon flexible fairings and helical ridges. In general, the available data show that all of these methods do, in fact, suppress vortex-induced vibrations to a greater or lesser degree. However, because of the diverse way in which suppression effectiveness has been measured, comparisons among different types of devices are difficult to make. Criteria for such comparisons are suggested. Relatively few measurements of the effects of strumming suppression devices on the drag of a cable or cylinder have been reported. The available data indicate that a large drag penalty may be incurred by use of such devices, depending on the configuration employed.

CONTENTS

INTRODUCTION

The Civil Engineering Laboratory (CEL), under the sponsorship of the Naval Facilities Engineering Command, (NAVFAC), is engaged in a program of research concerning the dynamics of cables and cable structures in the deep ocean. The program considers two specific problem areas: (1) the relatively small amplitude, high frequency cable vibrations due to periodic lift forces induced by vortex shedding (generally termed "strumming"); and (2) the large displacement, relatively low frequency or transient response due to disturbances during implantment or while in place on the ocean floor. When on the ocean floor the disturbances are due to shock waves or unsteady hydrodynamic forces associated with geostrophic, tidal, inertial, or density flows. In both parts of the program, the objective is the development of effective methods for the analysis and design of subsurface cable structures.

The vortex-excited vibration of cables is a commonly observed phenomenon in the ocean. This motion frequently results in degraded acoustic or environmental sensor performance and accelerated fatigue of structural elements. Further, the drag of a strumming cable is significantly higher than that of a nonvibrating cable, producing higher stresses in the elements and greater distortion of an array in a given current field. An integral part of the research into cable strumming in this program is the development of effective techniques to suppress the flow-excited motions of cables.

An extensive survey of existing literature on the suppression of vortex-induced motion was made recently at CEL [1] and an annotated bibliography was prepared. The treatment of the analysis of cable strumming suppression to date has been largely empirical with little or no theoretical consideration. Therefore, this initial effort has been extended to analyze the available reports to determine the ability of the various devices to suppress cable strumming, to compare their effectiveness in doing so, and to assess the effects of these devices on the drag of the cables.

Of primary concern in determining the characteristics of a device to suppress cable strumming are the environmental and handling conditions to be encountered. As defined by the Cable Dynamics Program Research Plan [2], the device must be easily handled, durable, cost-effective relative to cable cost, and able to suppress strumming in currents up to 1 knot (0.52 m/s.) The devices which presently appear to have the

best probability of meeting these requirements are: hair fairing*, fringe fairing, ribbon fairing, and longitudinal or helical ridges.

This report presents the following information:

1. The flow parameters which influence vortex-induced cable vibration are briefly discussed. This subject is covered extensively in the literature, and no attempt is made to present a complete review of cable vibration.

2. Each type of device is discussed separately, relevant available data are presented, and the present status of experimentation is given.

3. Experimental data for each of the four classes of devices are presented to provide a comparison of the behavior of the devices and of the effectiveness of the devices relative to each other.

Existing data generally provide only the vortex-induced acceleration or displacement of equivalent faired and unfaired cables and a comparison of these quantities; drag data may or may not be available. In any case, only the overall strumming reduction qualities of a particular configuration are recorded; no data or presentation of data attempts to indicate which structural or flow parameters are being modified by the device to suppress strumming. However, it is clear that interpretation of the modifications to the structural and flow parameters is essential for an understanding of the processes by which strumming suppression is achieved. It is the intent of the strumming suppression portion of the NAVFAC/CEL Cable Dynamics Program to determine which parameters or combination of parameters control the effectiveness of a suppression device. The data in this report and that generated by CEL cable experiments will be used to meet this goal.

VORTEX-INDUCED CABLE VIBRATIONS

As a fluid flows past a submerged body, viscosity causes the fluid at the surface of the body to be at rest with respect to the body and a shear and velocity gradient to exist within a boundary layer. Further, on the lee side of a submerged body an adverse pressure gradient exists which decelerates the flow. The combination of viscosity and an adverse pressure gradient results in the reduction of the velocity gradient normal to the body; in the case of bluff bodies, such as a cylinder or cable, this velocity gradient becomes zero at some point on the surface and the flow separates from the body. The flow

*The term "fairing" for suppression devices is a generic term that comes from early drag-reducing cable experiments with streamlining devices (or fairings).

separation gives rise to the development behind the body of a wake, the configuration of which is dependent on the dimensionless Reynolds number, which is defined as:

$$Re = \frac{UD}{\nu}$$

where U is the freestream velocity, D is a characteristic length, and ν is the kinematic viscosity of the fluid, in a consistent set of units.

The formation of vortices in the wake of a circular cylinder has been theoretically presented as the "vortex street" formed by the alternate shedding of vortices with a definite periodicity, which is dependent on the Reynolds number of the flow. This periodicity in the wake is quantified in terms of the Strouhal number,

$$S = \frac{fD}{U}$$

where f is the shedding frequency. In the range $4 \times 10^2 \leq Re \leq 2 \times 10^5$ the vortex shedding is regular and the Strouhal number is approximately 0.21. It has been shown [3], that a periodic wake appears at Re = 40; the wake is stable and regular up to Re = 150; between Re = 150 and Re = 300 the vortices gain energy and begin to interact; and above Re = 300 an irregular wake exists.

As a consequence of the wake formation there is a momentum loss which results in a drag force. Further, due to the periodic vortex formation, an instantaneous pressure differential exists, resulting in a periodic lift force perpendicular to the freestream direction of fluid flow. The strumming of a cable is the elastic structural response to this periodic lift force. The primary objective of the cable strumming portion of the Cable Dynamics Program is to investigate and predict the interaction between the elastic cable and the vortex-induced forces.

SUPPRESSION DEVICES

General

As discussed previously, the four types of suppression devices which appear to meet the program requirements (hair, fringe, ribbon, ridge) have been studied for their strumming suppression effectiveness by various investigators. The annotated bibliography [1] discusses a variety of suppression devices; however, many of the devices are not adaptable to a cable, and others are not feasible from a handling and logistics point of view when long cables - up to 20,000 feet (6096 m) - are being used. Ideally, the suppression device should be attached along the entire length of cable or a portion thereof during manufacture;

In addition, it is desirable to develop the capability to suppress strumming on an existing cable. Fringe fairing, hair fairing, ribbons, and helical ridges meet the requirements of a suppression device for moored arrays; therefore, a closer look at these devices was warranted.

The vibrations of a cylinder or cable can be substantially reduced by utilizing any one of the above devices. A helical device, whether a ridge, hair, fringe, or ribbons, tends to break up the spanwise coherence of the vortices by causing a variable location of the separation point. The adverse pressure gradient may also be reduced if the boundary layer is induced to turbulence. The trailing - and to some extent, helical-fringe, hair, and ribbons interfere with the vortex interaction in the near wake and disrupt the vortex formation length. The exact manner by which strumming is reduced is not generally well-established since there is a very complex pattern to the vortex disturbances; however, suppression effectiveness usually can be increased or decreased, depending on the geometry of each device.

Table 1 lists the geometric and material parameters which can be varied for each device. Structural and fluid dynamic parameters which are varied or determined experimentally are listed in Table 2.

The variation of the parameters listed in Tables 1 and 2 affects the ability of a device to suppress strumming; therefore, the parameters are important for determining the mechanism of strumming suppression and for comparision of suppression results with other devices or configurations of the same device.

The majority of tests conducted to date have measured the acceleration at various points along the cable when both the faired and unfaired cables are at the bare cable resonance condition. This ignores the change in resonant frequency of the faired cable from that of the unfaired cable. Consideration of changes in virtual mass or the logarithmic decrement of damping have not been addressed in studies to date, although the change in drag due to fairing has been reported. Generally, tests have not been made to determine the parameters which influence suppression, but rather to compare the strumming suppression qualities of the various devices. The sections which follow present details of the studies which have been conducted utilizing fringe fairing, hair fairing, ribbons or helical ridges.

Fringe Fairing

The term "fringe" refers to a fairing which has bunched tufts of strands of flexible material (such as polypropylene or nylon) attached to the cable helically or longitudinally. A typical longitudinal attachment is illustrated in Figure 1. This configuration is referred to as "trailing" fringe since the fringe is nominally along the downstream side of the cable and "trails" in the flow.

Nylon Rope Thongs. Kelly and Goff [4] utilized nylon rope thongs of various lengths and spacings (Figure 2) in an attempt to reduce cable vibrations. Their particular configuration was designed for systems towed at high speeds. A normal drag coefficient for each configuration was determined from the length and diameter of the cable, measured depth of the outboard end, weight, design lift-drag ratio, lift coefficient of the depressor, and drag depth of the recorder. A visual observation of the vibration amplitude of the cable was made during the initial testing and a vibration analyzer was used to measure the predominant frequency in subsequent tests. The results of the tests of this fairing are shown in Table 3, where C_D is the normal coefficient of drag. The data are limited in their usefulness and provide only a qualitative assessment of this fairing.

Tufted Fibers. In 1970, the Naval Underwater Systems Center (NUSC) initiated a cable development program for suspended sensor systems [5]. NUSC design criteria for a general family of suspended sensor systems required high reliability, stability, and quietness from the cable. Drag reduction was desirable, but not mandatory. The initial effort utilized a ribbon fairing, but the development of Kevlar cables indicated that a fringe-type fairing could be woven into the outer jacket during braiding. Wall Rope Works has developed a technique to incorporate tufts of yarn up to 7 inches (177.8mm) long at 1-inch (25.4mm) spacings in the cable outer braid. To date, polypropylene, nylon and monofilament polyester fibers have been used at a reported cost of $1.00/foot (304.8mm) to fair a cable. An "acceptable level of strumming" was reported in three 1,000-foot (305 m) lengths of 0.66-inch (17 mm) diameter, double-armored, steel tow cable with Wall Rope fringe fairing tested in the summer of 1974 by NUSC and Woods Hole Oceanographic Institute (WHOI) [5]. Acoustic and mechanical performance of a 0.75-inch (19.1 mm) diameter fringe-faired Kevlar 29 cable-3-inch-(7.6 m-) long polypropylene tufts spaced 1 inch (25.4 mm) apart - used in 15,000-foot (4572 m) WHOI and 4,600-foot (1402 m) NUSC arrays have been reported to be excellent (5). WHOI is presently preparing a report on the performance of the 15,000-foot (4572 m) moored array. The fairing system has now been used to reduce strumming on the Moored Acoustic Buoy System (MABS) and the Telemetering Acoustic Buoy System (TABS). The NUSC cable program has not attempted to modify the fringe fairing to attain maximum strum reduction with the least amount of materials and drag.

Polyvinyl Chloride Fibers. WHOI has tested faired and unfaired cables suspended in 60 feet (18.3 m) of water off the WHOI dock [6] in tidal currents to 1.5 knots (0.77 m/s). Bundles of polyvinyl chloride (PVC) fibers were woven into the outer jacket of a 0.375-inch (9.5 mm) diameter Kevlar cable; the fairing was 5.5 inches (140 mm) long, and the tufts were spaced 0.5 inches (12.7 mm) apart. Tests to determine strumming reduction dependence on tuft pattern density were conducted

by removing portions of the tufts. Figure 3 shows the results of the experimentation. The data show a great deal of scatter; however, the results do indicate that the fringe fairing does reduce cable strumming.

Polypropylene Fringe. The drag associated with the Wall Rope Works faired cable tested by WHOI and NUSC was investigated in the Massachussets Institute of Technology (MIT) water tunnel [7]. A cantilevered steel rod with a fringed dacron jacket was used to simulate a cable. A polypropylene fringe 6.5 inches (165.1 mm) long with 1.0-inch (25.4 mm) spacing was used in the tests. Drag, vibration frequency, and vibration amplitude were measured at various flow velocities - 16 velocity runs from 0.54 ft/s to 15.75 ft/s (0.17 m/s to 4.8 m/s). At each velocity the cylinder was rotated up to a maximum of 765 degrees to simulate the possible wrapping that may occur in the ocean. Figures 4, 5, 6, and 7 present the data from this experiment. In the range of velocities where the bare cylinder strummed, 5 to 13 ft/s (1.5 to 4 m/s), the drag on the nonrotated faired cylinder (angle of rotation is 000 degrees) is less than that of the bare cylinder, and the maximum amplitude of vibration relative to the bare cylinder was reduced by 300%; i.e., from 2.25 to 0.75 diameters. The drag at other angles of rotation increased above that for the nonrotated cylinder, but in all cases the fairing reduced the maximum amplitude of vibration relative to that of the bare cylinder. In some cases the amplitude of vibration for angles of rotation greater than zero was smaller than at an angle of 000 degrees (see Figure 5).

Helix Wrap. Two series of tests were conducted by General Electric and the U.S. Navy on Wall Rope Works fringe fairing applied longitudinally and spirally to a cable. Polyester monofilament and polypropylene fringe materials were tested. Only the helix wrap of fringe fairing was tested in the second series of tests in December 1975.

Table 4 shows the range of parameters in the first tests; values of the drag coefficient were determined for each cable at bare cable resonance and the amplitude of acceleration of the bare and faired cables were determined for the first, second, and third harmonics. The acceleration was reduced at all three harmonics, but a greater reduction was seen for the first and third harmonics. No shifting of energy between harmonics was noted. The drag coefficient data exhibited considerable scatter, ranging from 0.7 to 1.9 for the bare cable and from 2.0 to 6.0 for the faired cable, depending on the material and geometry.

Based on these experiments, a helix-wrapped polypropylene fringe fairing was tested further. Table 5 provides a summary of parameters for the helix-wrapped fringe fairing, and Figures 8 and 9 compare the drag coefficient for various fringe lengths and spacings as a function of Reynolds number. Acceleration data were taken; however, these have not been reduced to date. The drag results indicate that the helical wrap of fringe does increase the drag coefficient above

that of the bare strumming cable; however, the drag coefficient was comparable to that found in the earlier General Electric experiments [8] for a longitudinally fringe-faired cable. Drag dependency on angle of orientation was not exhibited when the tufts were cut back, but when two-thirds of the tufts were removed, the drag at 60 degrees was approximately twice that at an angle of 90 degrees. These data are being analyzed further at the present time.

The MIT testing program is an extension of earlier tests conducted in 1974 and the summer of 1975 [9]. This work was supported by a grant from the Ocean Science and Technology Divsiion of the Office of Naval Research. In the first series of tests bare cable strum tests were conducted in tidal currents up to 3.0 ft/s (0.91 m/s). A 76.5-foot (23.3-m) cable was suspended parallel to the bottom; tension, acceleration, and displacement measurements were recorded. As part of the experiment, a faired Kevlar cable was tested simultaneously with an unfaired Kevlar cable to determine the reduction in strumming. Only one test was made with the fairing to gain qualitative information into the strum reduction achieved by the fairing in field conditions. Table 6 is a summary of the test parameters.

MIT's second series of experiments were conducted the latter part of June and early July of 1976 [10] utilizing faired cable samples from Wall Rope Works, Philadelphia Resins Corporation, four of which were supplied by the Civil Engineering Laboratory. The experimental configuration was identical to the 1975 experiments; however, the fringe fairing was investigated by varying the length and spacing of the fairing. Results from this test have not been published.

Hair Fairing

The term "hair" fairing, as used in this report, includes any fiber fairing which is not bound together in tufts to form a fringe. The hair may be "fringe" in appearance, but it will be composed of individual fibers attached to the cable. Some of the types of fairings which fall in this class are Environmental Devices Corporation's (Endeco) "Haired Fairing", Philadelphia Resin Corporation's "fuzzy" fairing, and Prodesco, Inc's fairing.

"Haired Fairing," introduced by BRAINCON [11] listed among its attributes: (1) reduced cable drag, (2) reduced acoustic noise, (3) reduced cable vibration, and (4) reduced cable fatigue. The faired cable, shown in Figure 10, was designed to be wound on a standard winch and sheaved over standard cable blocks. Figure 11 shows the results of tests with the faired cable as published by BRAINCON. This fairing is now being manufactured by ENDECO, Marion, Massachusetts.

Kelly and Goff (16) tested BRAINCON's Haired Fairing and a cloth hair in a towed configuration at Reynolds numbers of 6.3×10^4 and 1.2×10^5. A double fairing (hair longitudinally 180 degrees apart) was supplied by BRAINCON for testing. Drag coefficient was determined

from the length and diameter of the sample, measured depth of the outboard end, weight, design lift-drag ratio, lift coefficient of the depressor, and drag of the depth recorder. Tow speed versus towing depth graphs were plotted for the fairings tested. Visual observation of strumming amplitude indicated that no reduction was obtained using the cloth hair fairing; no strumming suppression data were reported for the BRAINCON fairing.

During the summer of 1974 a cable strumming suppression study was conducted at the Naval Undersea Center (NUC) [12], following work done previously utilizing a helical ridge suppression device. The BRAINCON Haired Fairing was the only haired fairing tested. The test model was a 20-foot (6.10 m) length of polyvinyl chloride pipe with a BRAINCON faired cable attached longitudinally along the trailing edge of the pipe. Vertical and horizontal accelerations were measured at the midpoint of the pipe, and simultaneous tension readings were taken at each end of the pipe using two matched load cells. Tests were conducted at angles of 15, 10, and 5 degrees. Both constant acceleration - from 4 to 16 ft/s (1.2 to 4.9 m/s) - and constant speed - 6, 10, and 14 ft/s (1.8, 3.1, 4.3 m/s) - tests were made.

The data from the acceleration runs were used to give a qualitative indication of the strumming reduction properties of the various fairings. The constant-speed data were reduced to give peak line levels of spectra of summation tension and vertical accelerometer readings at each angle of inclination for each speed run. Axial and tangential drag coefficients were determined for each angle of inclination as a function of Reynolds number. The BRAINCON fairing was found to be quite effective in suppressing strumming and exhibited a drag coefficient of from 0.5 to 0.9.

The drag behavior and strum reduction of several devices is discussed briefly in a report by Dale, McCandless and Holler [13]. A haired fairing consisting of no. 50 grade cotton thread was used with the hairs oriented spirally on a 9-inch (228-mm) pitch. Figures 12 and 13 illustrate the drag coefficient and strum force data as a function of Reynolds number.

As part of the NUSC cable development program discussed in the previous section a contract was issued to Prodesco, Inc. to develop a fabric-backed fairing which could be attached helically around a cable. The resulting material has a polyester tape body 5/8 inches (0.016m) wide with 3-inch (0.076-m) polypropylene fibers protruding from each side. NUSC elected to use the Wall Rope Works fringe fairing discussed previously based on its success and did not utilize the Prodesco fairing.

WHOI [6] tested the Prodesco fairing during the strumming suppression study discussed previously. The results of this study are summarized in Figure 14 which shows the strumming suppression of Prodesco fairing compared with three ribbon fairings. The large scatter in the data necessarily makes interpretation of the data

qualitative in nature. Essentially, it can be stated that the fairing does reduce strumming, but that the amount of reduction is not clearly discernible.

Philadelphia Resin Corporation is developing a haired (brush) fairing (Figure 15) for the Naval Research Laboratory. Previously, Philadelphia Resin utilized chenille to make a fuzzy fairing; the strumming suppression characteristics of both fairings have yet to be reported.

Ribbon Fairing

Ribbons attached to a cable either helically or longitudinally have been used to suppress strumming. Ribbons attached longitudinally were used in the initial work at NUSC [5] for the NAVFAC Cable Development Program mentioned previously. South Bay Cable Company investigated methods to attach 0.010-inch (0.25 mm) thick, 2-inch (50.8 mm) wide, 6-inch (152.4 mm) long polyurethane ribbons to a 0.455-inch (11.6 mm) diameter polyurethane jacketed cable. Thirty-foot-long samples were tested from a pier at NUSC in currents up to 1 knot (0.52mm/s), with favorable strumming suppression results. Subsequently 16,000 feet (4877 m) of the faired cable was tested at sea and found to provide "good" acoustic and mechanical performance; handling was satisfactory and ribbon loss was minimal. No attempt was made to reconfigure the ribbon fairing to obtain the same suppression with less ribbon or to see if better suppression could be obtained. During the development of Kevlar cables it became evident that a fringe fairing could be attached without the plastic jacket required by the ribbon fairing; therefore, a Kevlar fringed fairing was developed in lieu of a ribbon fairing.

In work conducted at the David Taylor Naval Research and Development Center in Washington, D.C. (DTNSRDC) in 1971 [14] both bare and ribbon faired cables were studied to determine cable vibration frequency and amplitude. A 0.015-inch-(0.38-mm-) thick polyurethane sheet was used to fabricate the ribbon in all the experiments; the ribbons were attached by inserting them under two outer strands of a double armored steel cable. The lay of the cable resulted in longitudinally attached ribbons spiraling along the cable length; the effect of the spiral was not studied. Accelerometers and a force gage were placed on the cable, as shown in Figure 16.

The results of the tests are shown in Tables 7 through 12. The notation for ribbon configuration gives ribbon length by width by spacing - all in terms of cable diameters. The peak in the power spectrum of the transverse acceleration of the 0.35 inch (8.9 mm) or 0.5 inch (12.7 mm) diameter cable, tensioned to 1,200 pounds (5338 N) and subjected to a flow of 6 knots (3.1 m/s) was used as the norm for

all subsequent tests with the faired cables. Data in the last column of Tables 7 through 12 represent the percentage of the bare cable acceleration for each ribbon configuration value and not the percent of reduction in strumming acceleration.

The report concludes that:

1. The ribbon-faired cable peak transverse acceleration is generally lower than the peak transverse acceleration of a bare cable.

2. The level of vibration is independent of ribbon length, provided the ribbon is between 6 and 10 diameters long.

3. The level of vibration is independent of ribbon spacing for spacing up to 2 or 3 diameters.

4. Ribbon 2 diameters wide more effectively reduces vibration than ribbon one diameter wide for an angle of inclination to the flow of 45 degrees. At an angle of inclination of 90 degrees, both ribbon widths were equally effective.

5. The configuration with maximum strumming suppression was 6 diameters long and 2 diameters wide with a spacing of 1 to 2 diameters.

During fiscal year 1974 DTNSRDC undertook a comprehensive program to develop the Hydromechanics Technology of Towed Arrays [15, 16]. Two of the program goals were (1) development of strum-suppressed towlines and (2) prediction of drag for high speed arrays and tow cables.

The strum suppression study was conducted with an 18-1/3-foot-(5.6-m-) long, 0.528-inch-(13.4-mm-) diameter, 24 x 24, double-armored cable. The cable was suspended between a pair of struts at a constant angle of 15 degrees to the horizontal (and thus to the flow velocity vector) and was tensioned to 500 pounds (2224-N). Accelerometers were placed at the midpoint and the quarter point. Table 13 gives the range of parameters tested.

The study concluded that the most effective ribbon configuration was 6 diameters long and 1 to 2 diameters wide. A 25% coverage was adequate to reduce the strum level to less than one-tenth of that of the bare cable. The shorter fairing produced a similar strum reduction but required a higher percentage of cable coverage.

The objective of the second phase of the DTNSRDC strumming reduction study was the determination of the hydrodynamic drag of the faired cable both in the tow tank and during sea tests [15]. The results were reported graphically for tow angle versus speed, kiting angle versus speed, and normal and tangential drag versus Reynolds number. The hydrodynamic force coefficient data are shown in Figure 17 and 18. The drag coefficient data shown in Figure 17 indicate that the ribbon configurations tested generally lead to a higher drag coefficient markedly so at higher Reynolds numbers (> 10^5). Compared with helical ridges discussed later in this report, the ribbon fairing drag is higher than the ridge which tends to be equal to or lower than bare cable drag.

In conjunction with the testing of other suppression devices at NUC, ribbon faired models supplies by the Zipper-tubing Company were tested. This particular fairing is designed so that it can be applied

to existing cables. The test arrangement is described in the previous section. The model characteristics are given in Table 14 and the results shown in Table 15. Table 15 gives the value of the normal drag coefficient and reduction in cable acceleration (expressed in decibels) for each Reynolds number and cable angle tested; the reduction in acceleration at 25 degrees is plotted in Figure 19. The bare pipe drag data are given in Table 15. Using the bare pipe hydrodynamic drag as reference, flags were found to generally reduce the normal drag coefficient while increasing the tangential drag coefficient. This change in hydrodynamic drag would have a large effect on tow cable angle and on tow cable tension which need to be considered when selecting a strum reduction method.

The WHOI series of experiments discussed in the two previous sections also included ribbons. The test results shown in Figures 14 and 20 are for the configurations shown in Figure 21. The ribbon fairings tested are as described below.

FSW (Fringe-Spiral-Wrap) - This fairing consisted of a strip of 0.006-inch (0.15 mm) polyurethane 8 inches (203 mm) wide, cut transversely to within 1.5 inches (38.1 mm) of one edge in strips 1.0 inch (25.4 mm) wide. This was wound and glued in a spiral wrap around the cable. The fairing length was reduced to 4.0 inches (101.6 mm) after testing the original.

NUSC - This was made of 2.0-inch (50.0 mm) wide polyurethane strips folded over and bonded to a polyurethane jacket which had been extended on to the cable. The flags had a length of about 5.0 inches (12.7 mm).

Rochester - 0.5-inch-(12.7mm) wide ribbons of polyurethane 9 inches (228.6mm) long were threaded under one strand of the outer layer of the steel cable. The ribbons were packed closely along the length.

Additional unpublished testing on ribbon and ribbon stubs for towed arrays was conducted at DTNSRDC in September 1974 and December 1975. The results of both of these studies are to be available during 1977. The angle between the cable axis and the flow was found to be 20 degrees in both of these studies.

Based on the earlier work at DTNSRDC [14] the Naval Coastal Systems Laboratory (NCSL) is utilizing a ribbon fairing, (Figure 22) on 150 feet (45.7m) of 650 feet (198.1m) sweep wires for mine-sweeping operations. Continental Wire Cable Corporation makes the faired cable for use by NCSL. NCSL has reported favorable results with the system as deployed.

Helical Ridge

One of the earlier studies of the suppression characteristics of helical ridges is that of P. Price [17]. His report primarily discusses the use of shrouds; however, five models with helical or longitudinal ridges (as depicted in Figure 23) were tested. Price found the strakes

to be ineffective suppressors; and, he states, the paralled wires and radial fins possessed only unidirectional effectiveness and hence would not prove to be satisfactory suppressors in a stack application. The most beneficial helical configuration was not sufficiently effective to merit further consideration.

The use of helical ridges for use on stacks and towers has received considerable attention at the National Physical Laboratory (NPL) in Teddington, England [18 through 24]. Beginning with the early work by Scruton and Walshe [19] helical ridge studies have been made of many stacks and towers to provide aerodynamic damping.

Primarily, a three-start helical ridge device has been studied; however, in work by Woodgate and Maybrey [24] 1-, 2-, 3-, and 6-start helical ridge systems were tested. In all the reports cited, the drag induced by the use of the ridges is not considered, except in that by Cowdrey and Lawes [18], Figures 24 and 25. The NPL work concluded that suppression of the vibration of a tower or stack can be achieved utilizing a three-start helical strake applied to the top one-third of the structure.

Weaver [25] investigated a four-start helical ridge system with a pitch of 12 diameters and a height of 0.08 diameters. Figures 26, 27, and 28 show the influence of the number of ridges, height of ridges, and the pitch of the ridges, where D is the cylinder diameter, C_{ks} is the maximum value of the fluctuating lift for a cylinder with ridges, and C_{kb} is the maximum value of the fluctuating lift for a bare cylinder. The tests indicated that an effective suppressor must have the following characteristics:

1. four helical windings
2. ridge diameter of D/16 to D/8
3. pitch of 8D to 16D

Weaver selected a height of 3D/32 and a pitch of 12D to reduce the lift force to a minimum.

Drag measurements on a circular cylinder fitted with vortex generators have been made [26]. The generators (ridges) were one-half times the boundary layer height, and an optimum location of 50 degrees either side of the front stagnation point was determined. Figure 29 shows a comparison of the drag coefficient for a smooth cylinder with that of a cylinder with vortex generators.

Dale McCandless, and Holler [13] reported tests of twisted pairs of cables. Cables of 0.057-inch (145-mm) diameter were used with a pitch of 15 diameters. Figures 12 and 13 show the strum reduction effectiveness and the drag coefficient as a function of Reynolds number.

The first series of NUC experiments [26] tested models of 1.31-inch (33.3-mm) OD PVC pipe (to simulate a taut cable) fitted with various combinations of helical ridges, both round and rectangular. Table 16 lists the model characteristics; Figure 30 shows the types of ridges used; and Table 17 lists the ridge cross-section parameters.

Measurements of the effectivcness of the ridges was done by comparing the highest amplitude of the accelerometer trace during acceleration runs.

Figure 31 shows the dependence of the amplitude of the accelerometer trace on ridge height to cable diameter ratio d/D for a fixed pitch; Figure 32 shows the dependence on ridge pitch to cable diameter ratio for a fixed ridge height; and Figure 33 indicates the dependence on ridge removal. For the one case tested with multiple ridges, no hydrodynamic benefit was noted. As would be expected, it was found that for equal effectiveness a rectangular ridge does not have to be as high as a roun' ridge.

Internatio. 1 Telephone and Telegraph (ITT), Cable-Hydrospace Division was contacted during the course of the investigation concerning the manufacture of a ridged cable. Three or more ridges were preferred for die design reasons, but no unreasonable ridge height or width dimension limitations seemed to exist for a direct extrusion process with helix reversals at regular intervals.

The second series of tests at NUC [12], as discussed previously, extended the earlier work with helical ridges to include tests on flags, hair, and ribbons. Acceleration runs and constant velocity runs were made. Data were reported for tension, cable acceleration and drag. Table 18 gives the characteristics of the helical ridge models tested. The results are given in Table 19 as the normal drag coefficient and acceleration reduction in decibels as a function of cable angle and Reynolds number. The data are plotted in Figure 34.

The towed array tests at DTNSRDC discussed in Section 3.4 (6,7) also investigated the use of helical ridges. The helix was reversed at the midpoint of the cable model; the models tested for their strum reduction are summarized in Tables 20 and 21.

The results of the tests are given as the reduction in cable acceleration as a function of P/D (pitch/diameter) and d/D. The components of acceleration for the first through sixth harmonics were considered. A pitch-to-diameter ratio of 15 to 20 was found to produce maximum effectiveness.

Drag characteristics of the DTNSRDC cables with a helix wire wrap [15] were determined in basin tests and at-sea tests. In the basin tests, a $d/D = 0.24$ was used with a $P/D = 15$; the helix was reversed every 10 feet. In the sea tests, a $d/D = 0.23$ was used with $P/D =$ 15, 20, and 30; the helix was reversed every 14 feet. Figures 35 and 17 give the normal and tangential drag of the cables tested.

The drag coefficient was determined from a triaxial force gauge; acceleration data were obtained through accelerometers placed at the midpoint, quarter-point and the three-quarter point on the cable. Acceleration components for the first through third harmonic were reduced from the data.

DISCUSSION

Criteria for Suppression Device Comparison

By far the most common method used to determine the effectiveness of a strumming suppression device is measurement of the acceleration at various points along a bare cable and comparison of these acceleration readings to those obtained with a suppression device attached to the cable. Some investigators have measured the amplitude of the cable displacement, both bare and faired, and used this as a basis for comparison. Obviously, if the acceleration component is zero for the even and odd harmonics, the cable displacement is also zero, so either method provides a valid comparison. A problem develops, however, when a comparison of data from the various investigators is attempted. No single parameter has been used by the various investigators to determine the quality of a device other than "Does it reduce strumming?" Comparing several devices during a series of experiments will indicate which devices reduced the strumming significantly more than others but may give no indication of the relative efficiency of the devices. The parameters listed in Table 1 can be configured to yield a good suppression device regardless of the type used; thus, two investigators may claim that two different devices reduce strumming by 30 decibels, but which is the more efficient?

Many investigators use acceleration or amplitude data to express the effectiveness of a suppression device. Although drag is not a measure of strumming effectiveness, it does enter into the efficiency of the device. That is, a device may eliminate strumming but induce a substantial drag; therefore, the efficiency of the device in reducing strumming but not adding a drag problem is compromised. Both drag and acceleration/amplitude data are needed to classify a particular suppression device.

Acceleration data are normally presented in decibels by

$$\beta = 20 \log Ac_1/Ac$$

where Ac_1 is the acceleration of the faired cable and Ac is the acceleration of a bare cable under the same test conditions. This quantity will be negative for reduction of the vibrations. The percentage in strumming reduction with respect to a bare cable will also be used in this report to provide a linear scaling.

Table 1 lists geometric parameters which can be varied for each type of device. In addition to these, there are three parameters common to all the investigations:

(1) Reynolds number of the flow based on the diameter of the bare cable and the free stream flow velocity

(2) Angle of attack of the flow relative to the longitudinal axis of the cable (in this report, a cable normal to the flow has an angle of 90 degrees)

(3) f/f_s where f is the natural frequency of the bare cable in the fluid and f_s is the Strouhal frequency (in this report the comparisons are based on $f/f_s = 1$)

The use of f/f_s takes into account the tension, virtual mass of the cable, and length of the cable; therefore, a comparison between independent studies with different cables, lengths, and tensions can be attempted.

Tables 22 through 25, Table 5, and Figures 36, 8, and 9 give the parameters considered in each study discussed and the values of the drag coefficient C_D and β. The value in parentheses in the β column is the percentage in strumming reduction relative to the bare cable.

Suppression Effectiveness

Figure 37 utilizes the data in Tables 22 through 25 to show the percentage in strumming reduction as a function of Reynolds number for fringe, hair, ribbon, and helical ridge fairings at all angles to the flow for which data are available (Re based on freestream velocity and bare cable diameter). It is apparent that suppression effectiveness is not so much a function of Reynolds number as it is a function of the type and configuration of the suppression device. Figure 38 considers only those tests for which the cable is perpendicular to the flow. A Reynolds number dependence is not evident.

The usual basis for comparison of different devices in the same series of experiments is acceleration reduction. For example, if a relative difference of 30 decibels were found between devices "A" and "B", the device with the greater magnitude of reduction was considered to be the better suppressor. In Figure 39 suppression devices are compared on the basis of a logarithmic scale; i.e., 20 log (Ac_1/Ac). The use of a decibel scale can be misleading since it is not a linear scale. Because strumming can affect the operation of acoustic devices, a decibel scale is an obvious choice for comparison; however, it must be realized that 5 decibels represents a 44% reduction with respect to the strumming of a bare cable. For each 5 decibels, an additional 44% reduction is achieved, and at a reduction of 40 decibels 99% of the bare cable strumming has been eliminated.

It is reasonable to consider the level to which strumming should be reduced in operational systems. For example, Griffin and Skop [27] specified a peak-to-peak displacement of 0.1 diameter as the threshold of strumming. If a 90% reduction in displacement amplitude is taken, on this basis, as an acceptable level of strumming, then only a 20-decibels reduction is required. In effect, as shown in Figures 38 and 39, the majority of devices discussed in this report effectively suppress strumming. Other aspects of the behavior of suppression devices (particularly the hydrodynamic drag) may govern the choice of fairing type for a particular application. For systems with acoustic sensors, however, the acceleration amplitude may be the most important consideration.

The drag coefficeints for all devices can be plotted versus Reynolds number (Figures 40 and 41). If each device tested were evaluated within a range of Reynolds numbers, then modified, and the sequence repeated, a family of curves would result. A good example of this is seen in Figures 8 and 9 for the recent General Electric data taken at DTNSRDC. Clearly, not enough drag data, within the Reynolds number range for moored arrays, are available.

For the discussion which follows, Tables 22 through 25 and Table 5 are used, although no specific reference is made.

Fringe Fairing. The most comprehensive data for this type of fairing are those of General Electric [8] and Cohen [7]. The initial work by G.E. indicates that either a trailing fringe or a helical fringe (both manufactured by Wall Rope Works) will suppress from 87% to 100% of the vibration, based on acceleration levels. The drag coefficient data show considerable scatter, and the reliability of the drag data may be doubtful. However, the drag data obtained in the Navy experiments conducted in December 1975 (Figures 8 and 9) are good and indicate a C_D of between 2.0 and 4.0 for a helical fringe. This is within the same range to be expected for a strumming bare cable. In either case, the total drag on the cable would be greater than that on a nonstrumming bare cable. Reconfiguration of the device for maximum suppression with least fringe would reduce the drag. This was attempted in the latest Navy experiment; however, test data have not been reduced at this time.

Cohen's [7] data indicate a trailing fringe will have about the same drag characteristics as a bare cable with a maximum amplification of 1.35 if the fringe becomes wrapped around the cable. Strum reductions, regardless of wrapping, range from 60% to 80%; this is consistent with the G.E. data. In either case suppression is obtained utilizing the Wall Rope Works fringe fairing.

Hair Fairing. Very few data exist for hair fairing except those for ENDECO's Haired Fairing. These data are for high Reynolds number ($\sim$Re = 10^5) and low angles of attack ($\sim$15 degrees). The drag data appear consistent (with C_d from 0.5 to 0.9 and the strumming suppression from 60% to 100% based on acceleration).

Philadelphia Resin Corporation brush fairing has not been experimentally tested and reported; however, experiments at MIT in June and July of 1976 utilized the brush fairing.

No data are available for ENDECO's Haired Fairing at 90 degrees to the flow.

Ribbon Fairing. DTNSRDC has made extensive tests of ribbon fairings for application to towed arrays. The ribbon and stub configurations obtained by DTNSRDC [15, 16] provides excellent suppression with a C_D in the range 2.0 to 6.0. Additional data were obtained in further tests (as yet unpublished) and should provide a design with maximum suppression with the least material. One test run was made with the

ribbon-faired cable normal to the flow, but excessive drag on the cable caused a failure of the test rig. Apparently, the configuration of ribbons and stubs for a moored array would need to be modified from that for a towed array. The fact that ribbons can provide suppression at 90 degrees is evident from the WHOI data [6]. The WHOI tests were conducted in open water, and control over the flow parameters was not sufficient to provide consistent data.

The zip-on ribbon fairing provided by the Zipper Tubing Company for NUC's testing [12] shows suppression characteristics equal to that of the fairing developed at DTNSRDC; the drag coefficient range of 0.75 to 1.3 is quite acceptable. The main problems with the zip-on fairing are handling and application on a long mooring cable.

Helical Ridge. Work has been conducted at NPL with three-start helical ridges; however, the presentation of the data does not lend itself to comparison with data taken subsequently in the United States. The NPL parameters are consistent with those used by Skop and Griffin [27] and provide a measure of what the ridges do to the response of the system. The region of instability of a cantilevered beam with helical ridges is reported as a function fo structural damping. Price's work [17] offers little information. Weavers' data [25] although difficult to compare to present work, does confirm the work done at NPL and indicates recommendation for a four-start helical strake with a height of 3/16 diameters and a pitch of 12 diameters.

Recent work was performed at DTNSRDC [16] and NUC [28, 12] comparing helical ridges with other types of suppression devices. DTNSRDC found the drag coefficient for the helical ridges considerably less (1.1 to 1.9) than the ribbon fairing, but they had less strumming reduction. The ribbons were selected for further study, and work with helical ridges was postponed. The NUC [28, 12] studies indicated a much higher drag than did the DTNSRDC study (1.0 - 4.0). Both studies were conducted at low angles of attack, and the NUC study found the helical ridge suppression effectiveness was reduced somewhat as the angle decreased from 25 to 5 degrees. The NUC reports do not indicate superiority of a helical ridge over ribbons or hair, nor do they indicate that a multistrake device would offer better suppression.

CONCLUSION

A review of Tables 22 through 25 indicate that all devices tested to date suppress strumming. The determination of which device to use is, therefore, usually based on user or investigator preference. Some insights about the various devices, however, can be obtained from the previous investigative work and they are listed below:

- Fabula's [12] data indicate that a single helical ridge is angle dependent; i.e., on the angle between the flow and the

longitudinal cable axis. This is to be expected since as the angle decreases less of the ridge is "seen" by the flow. Walshe [22] noted that with a three-start helical ridge system the strumming suppression characteristics are independent of orientation angle.

- The drag coefficient of helical fringe ranges from 2.0 to 6.0, whereas the trailing fringe tested by Cohen [7] was between 1.0 and 2.0.
- The drag coefficient for helical fringe fairing exhibits a strong dependence on Reynolds number (Figure 8). It is probable that as the flow velocity increases the fringe tends to lay down in the direction of flow thus reducing the apparent frontal area. Angle dependency is exhibited for helical fringe only when the fringe is thinned; apparently, the same effect as with a single helical ridge occurs.
- Reliable and consistent drag data for strumming suppression devices are lacking (as seen in Figures 40 and 41), particularly in the region of concern for moored array.
- Angle dependence of most devices has not been thoroughly investigated. Most studies have been performed either at 90 degrees to the flow or at a low angle simulating a towed configuration - but not both. Angle orientation needs to be considered in the design and application of the strumming suppression device.
- Helical ridges have been used successfully to reduce smoke stack and tower vibrations; however, NUC and DTNSRDC have shown the helical ridge to be less effective than ribbons, hair, or fringe. Helical ridges could, however, be easily extruded on long cables [28].
- DTNSRDC ribbon experiments have indicated a substantial drag differential between towed and moored arrays for the same ribbon configuration.
- Reynolds number does not appear to be a common parameter for distinguishing the strumming suppression effectiveness of various devices; however, for a single device C_D is a function of Reynolds number.
- A hierarchy for classifying devices by C_D is not evident from Figures 40 and 41. Strumming suppression device and vortex interaction should be studied to determine how the device affects the vortex formation, coherence, and strength.

The determination of a device's ability to suppress strumming cannot be achieved by simply placing the device on a cable and testing to see if strumming is suppressed. To pursue the problem economically and logically, a basic understanding of the fluid dynamic damping obtained from the various devices needs to be achieved. This will, in turn, lead to the efficient design of a strumming suppression system which meets the needs of a particular cable configuration.

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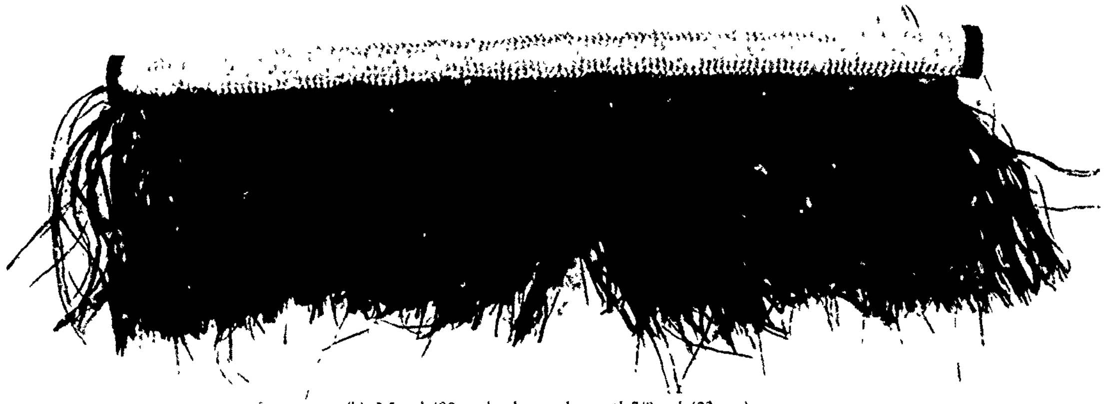
(a) 3 in (76-mm) nylon with 7/8-in (22-mm) spacing, cable diameter = 1/2 in 12.7 mm)



(b) 3.5-inch (89 mm) polypropylene with 7/8-inch (22-mm) spacing cable diameter = 5/8 inch (16 mm)

Figure 1. Wall Rope Works fringe fairing.

Figure 2. Thonged fairing, 8 inches (204 mm) long, 6/in. (from Reference 4).

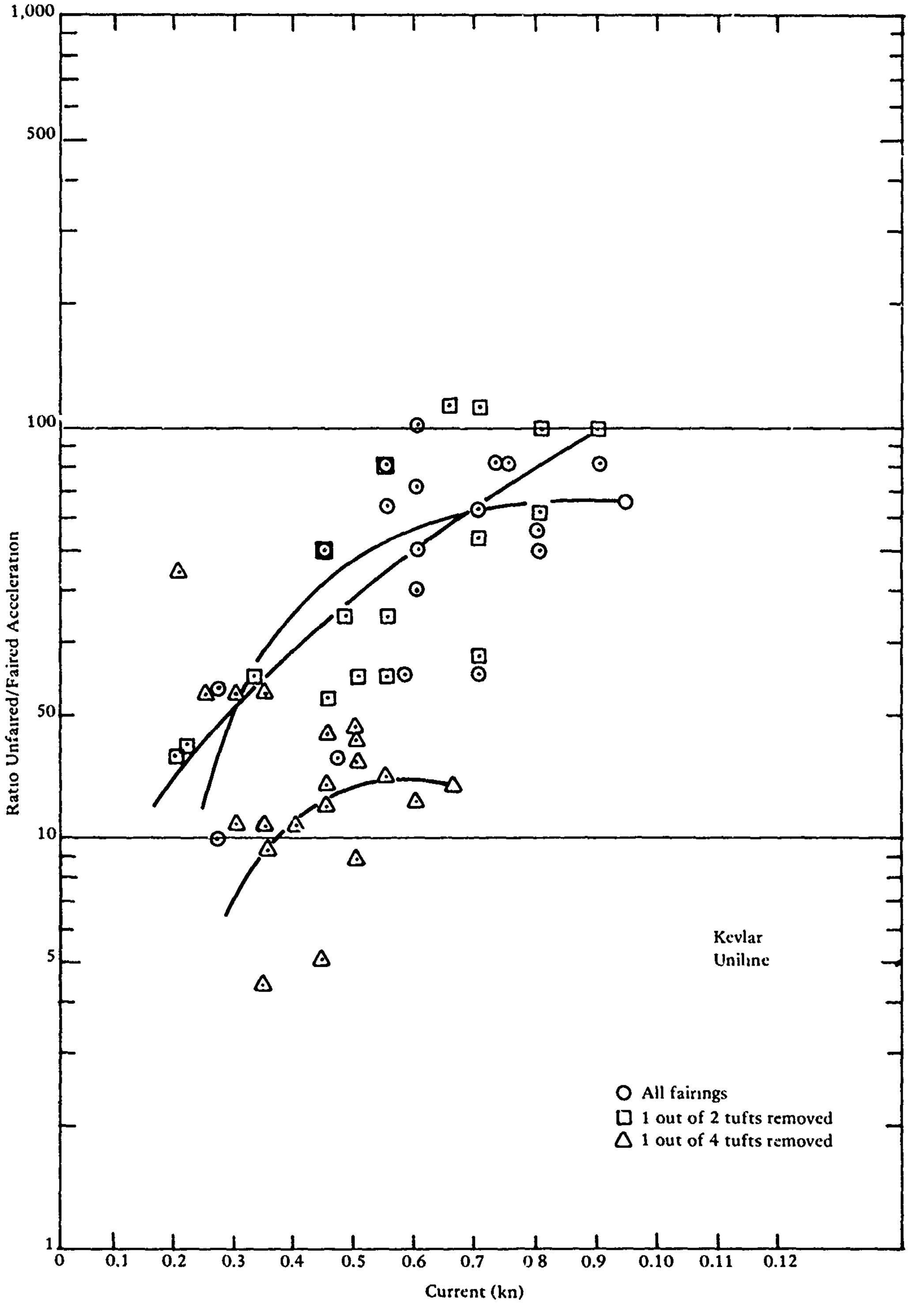


Figure 3. Effectiveness of fairing density on Kevlar line. (from Reference 6).

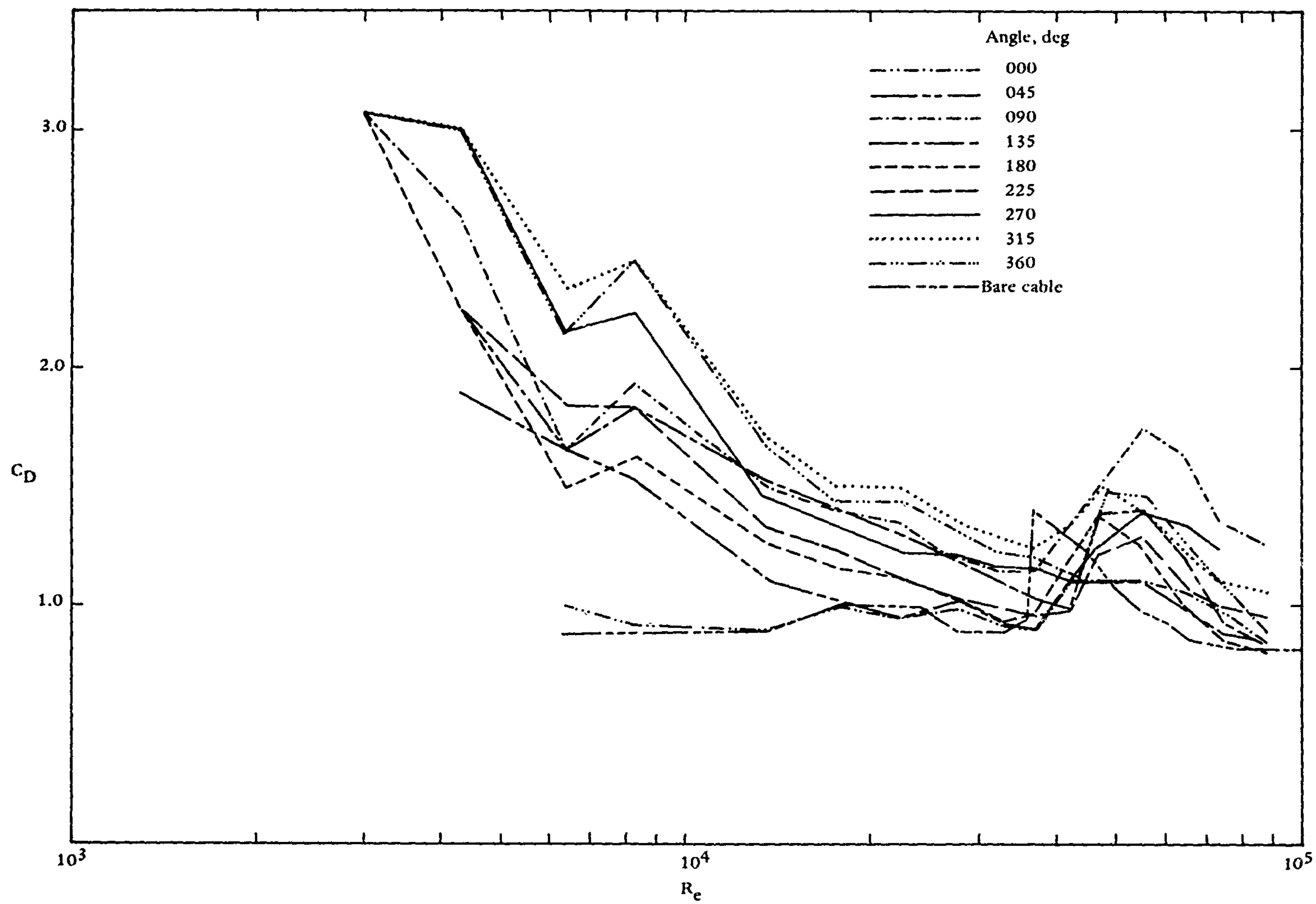


Figure 4. Faired model calculated drag coefficient (R_e based on bare cylinder diameter). (from Reference 7).

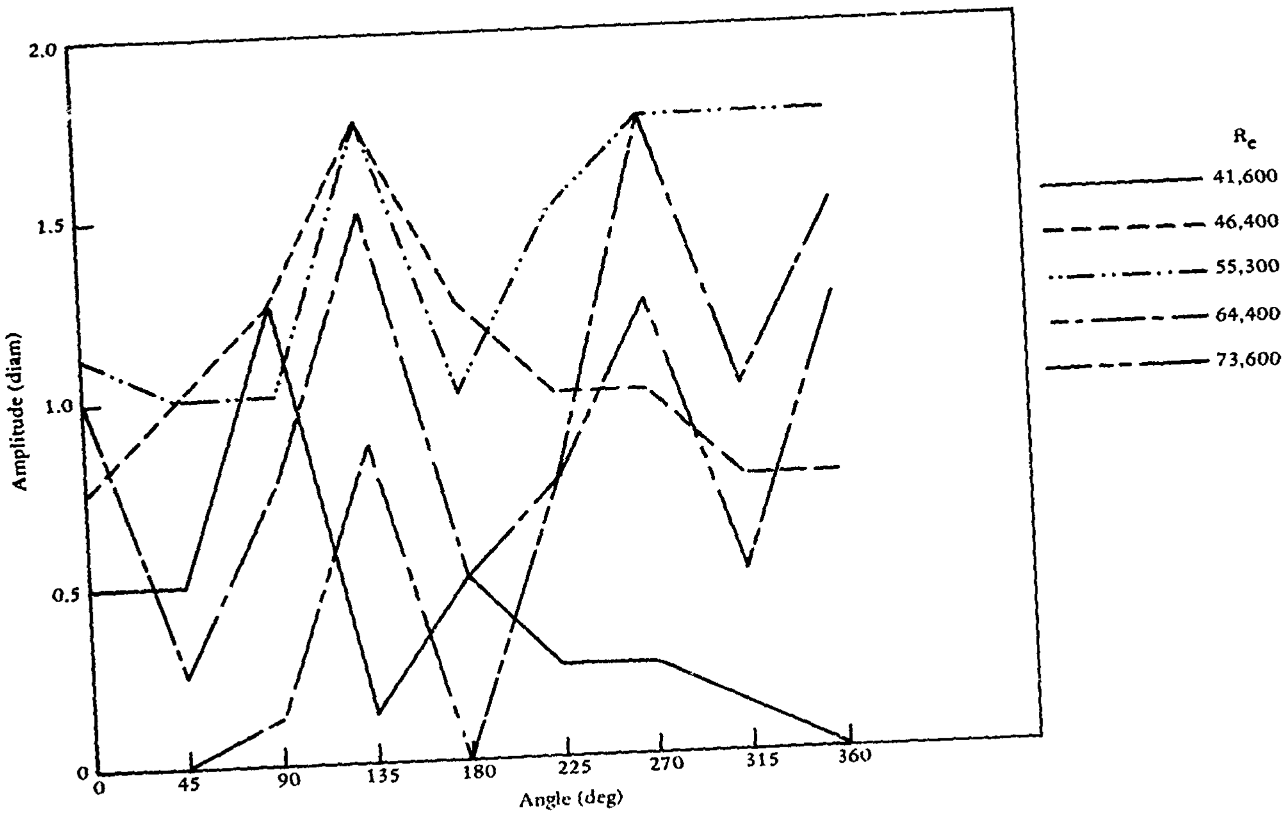


Figure 5. Amplitude of faired cable in diameters.
(from Reference 7).

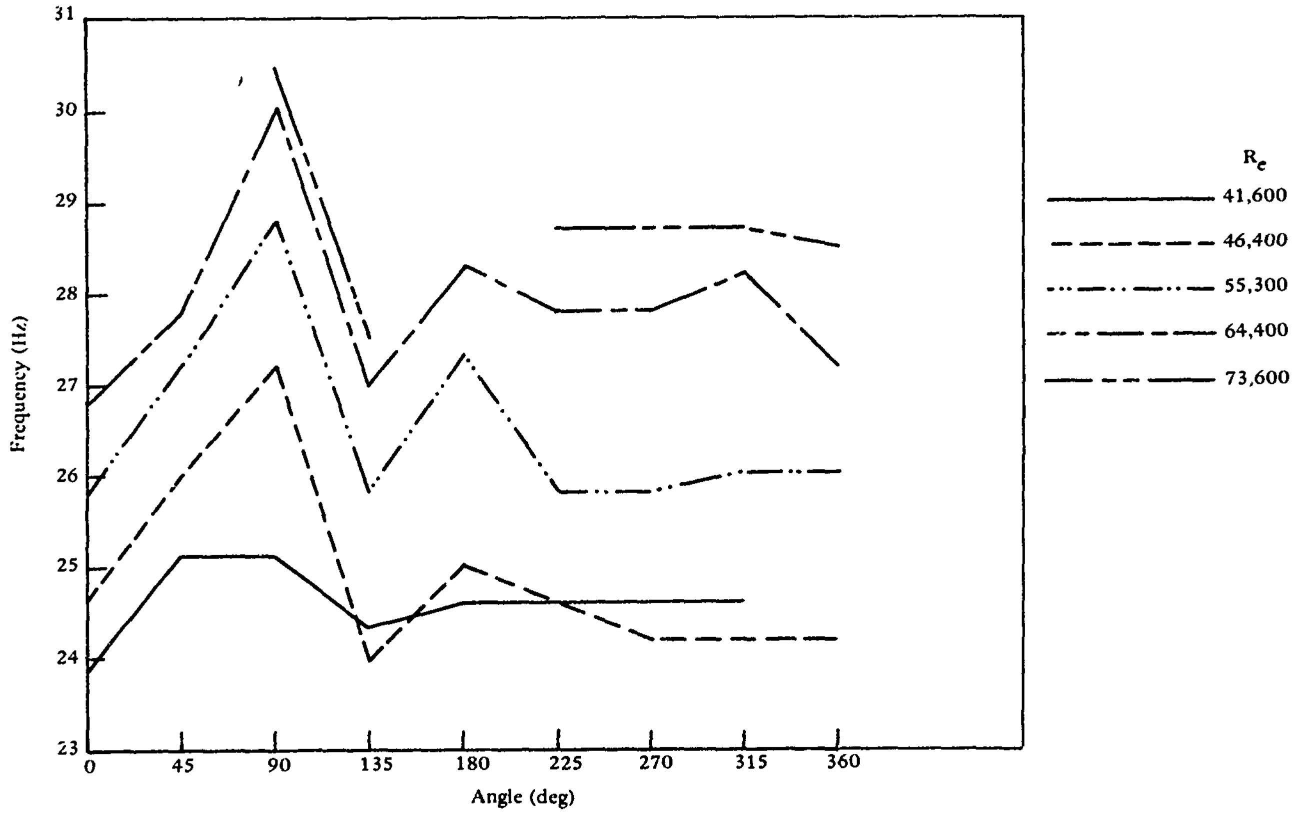


Figure 6. Frequence of faired model vibration.
(from Reference 7).

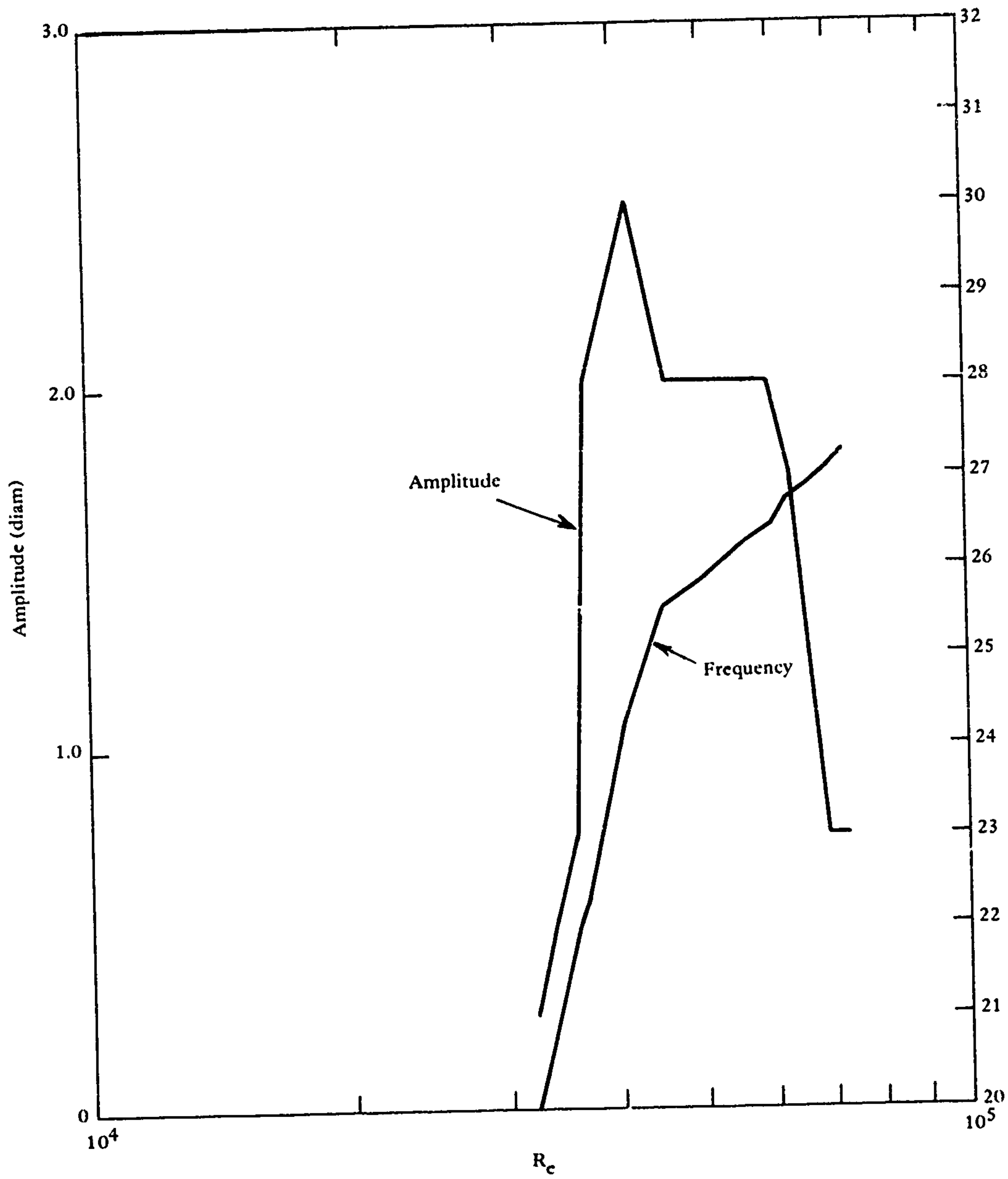


Figure 7. Amplitude and frequency for bare cylinder vibration. (from Reference 7).

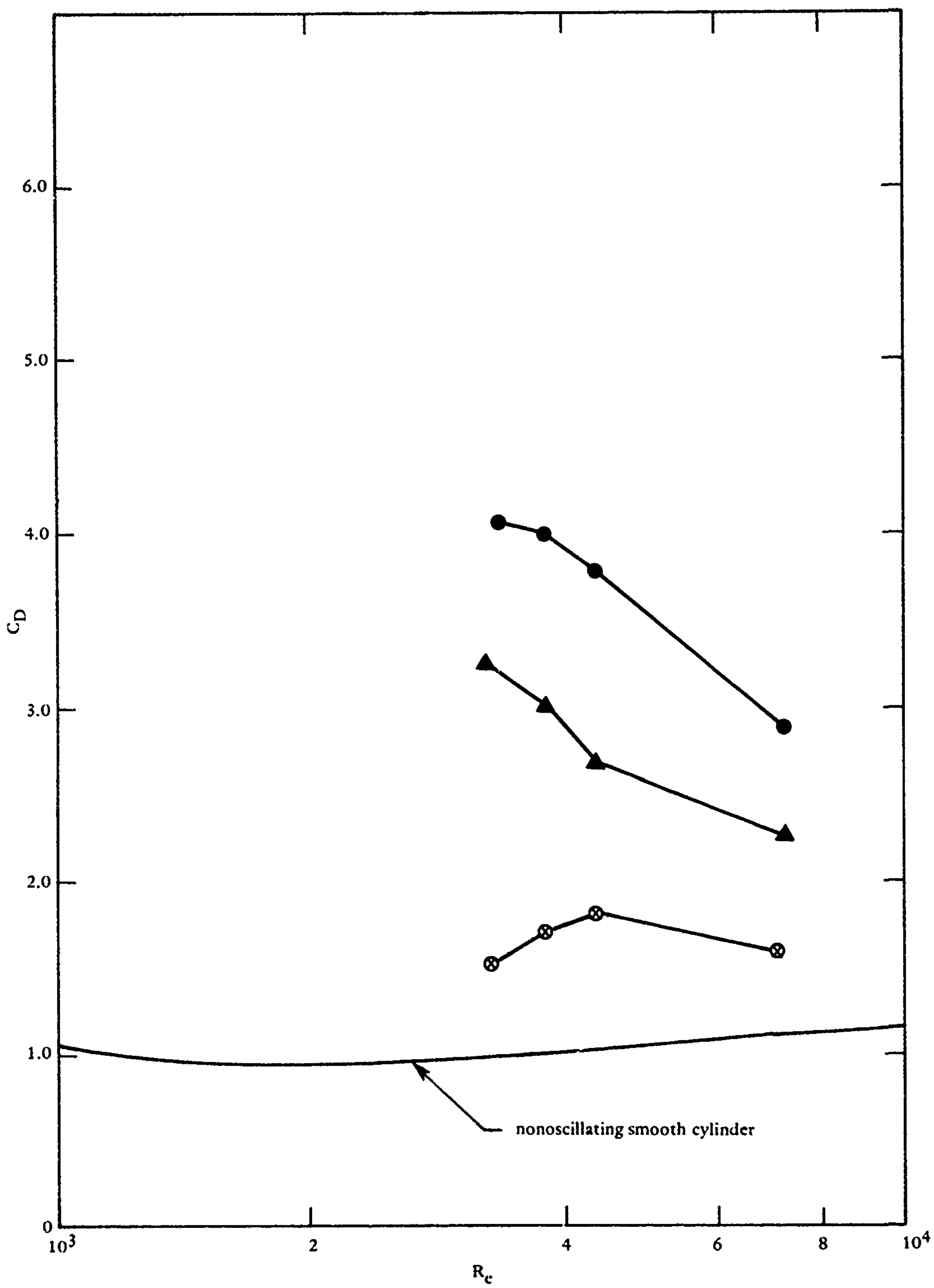


Figure 8. Results of normal drag on G. E. helically fringed cable with tow angle of 60 degrees. See Table 5 for key to symbols.

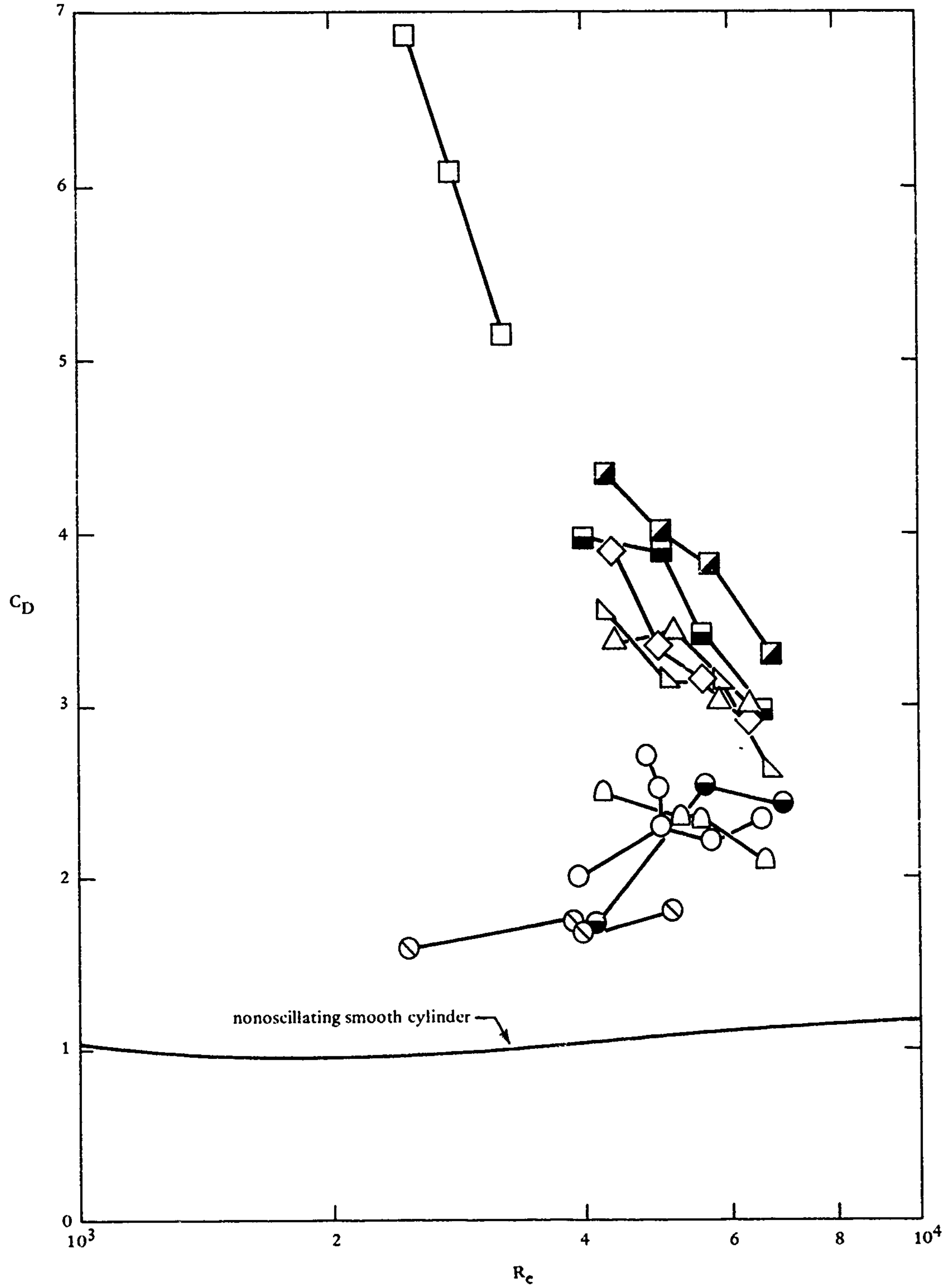


Figure 9. Results of normal drag on G. E. helically fringed cable with tow angle of 90 degrees. See Table 5 for key to symbols.

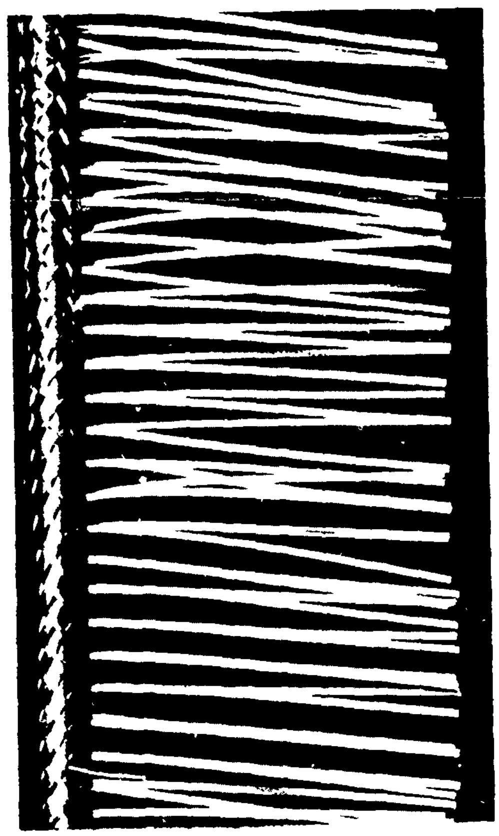


Figure 10. BRAINCON Haired Fairing.
(from Reference 11).

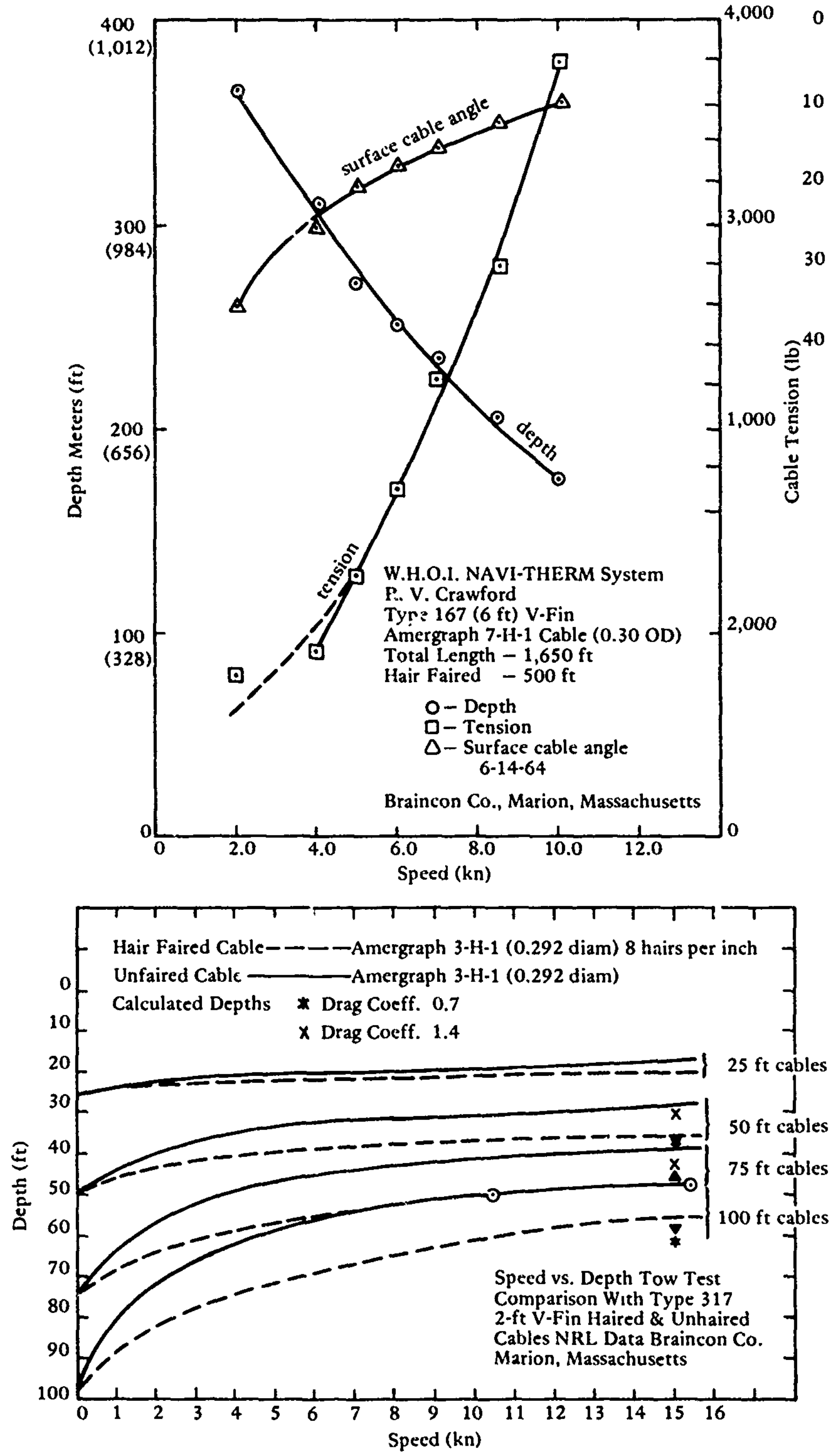


Figure 11. BRAINCON data sheet. (from Reference 11).

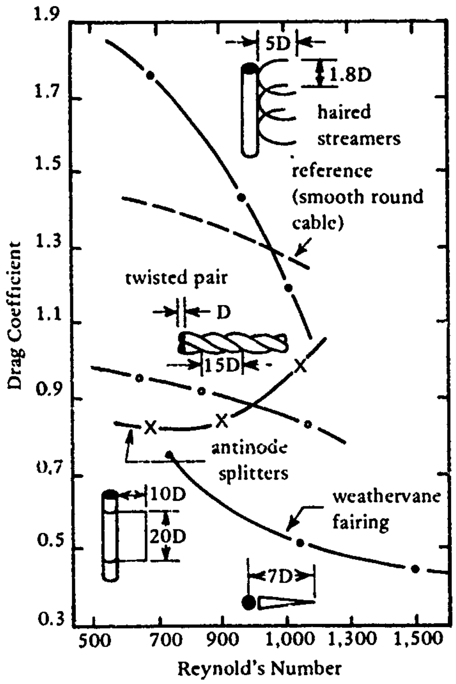


Figure 12. Drag characteristics of special cable designs. (from Reference 13).

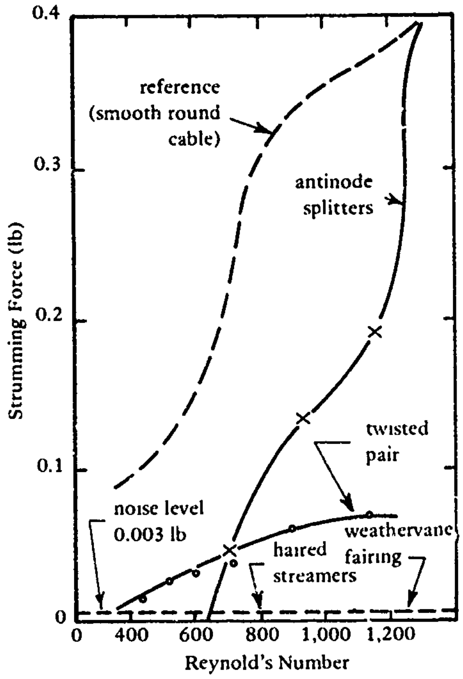


Figure 13. Strumming force characteristics of special cable designs. (from Reference 13).

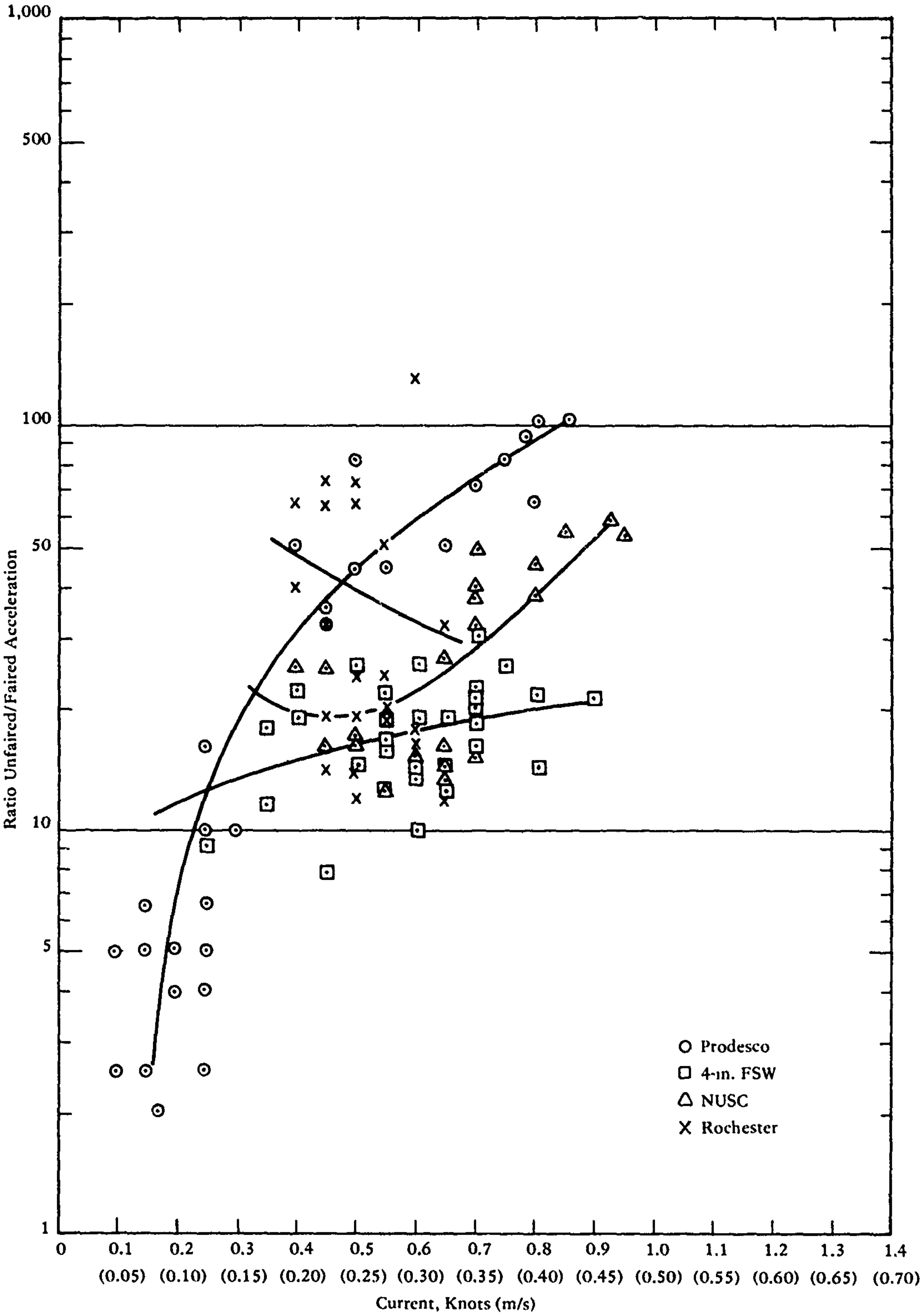


Figure 14. Acceleration ratios for four faired wire ropes. (from Reference 6).

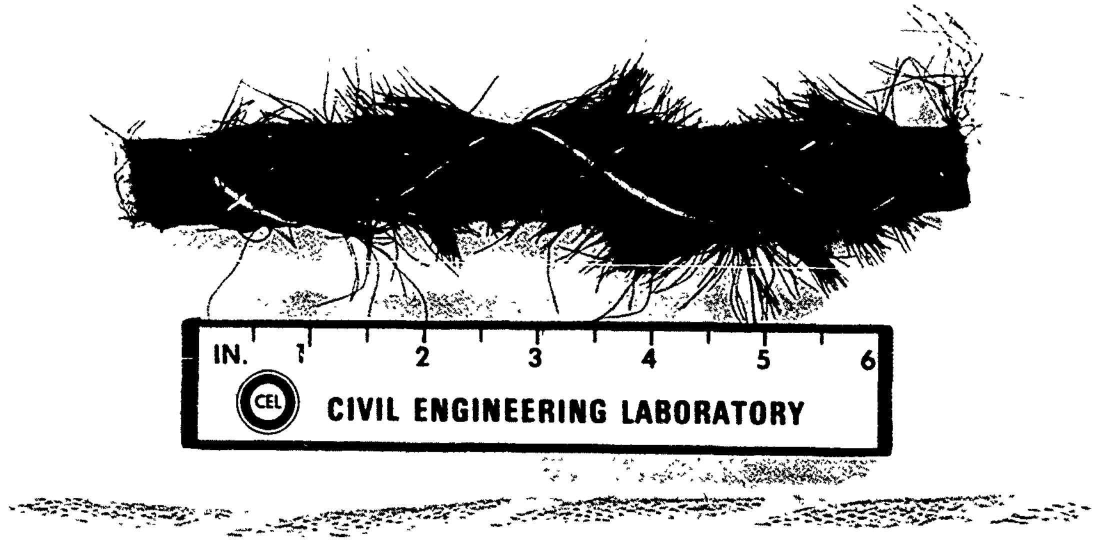


Figure 15. Philadelphia resin corporation haired fairing: top, brush fairing applied helically on 0.75-in. (19.2-mm) diameter cable; bottom, cotton fuzz applied helically on 0.25-in. (6.4-mm) diameter Kevlar cable.

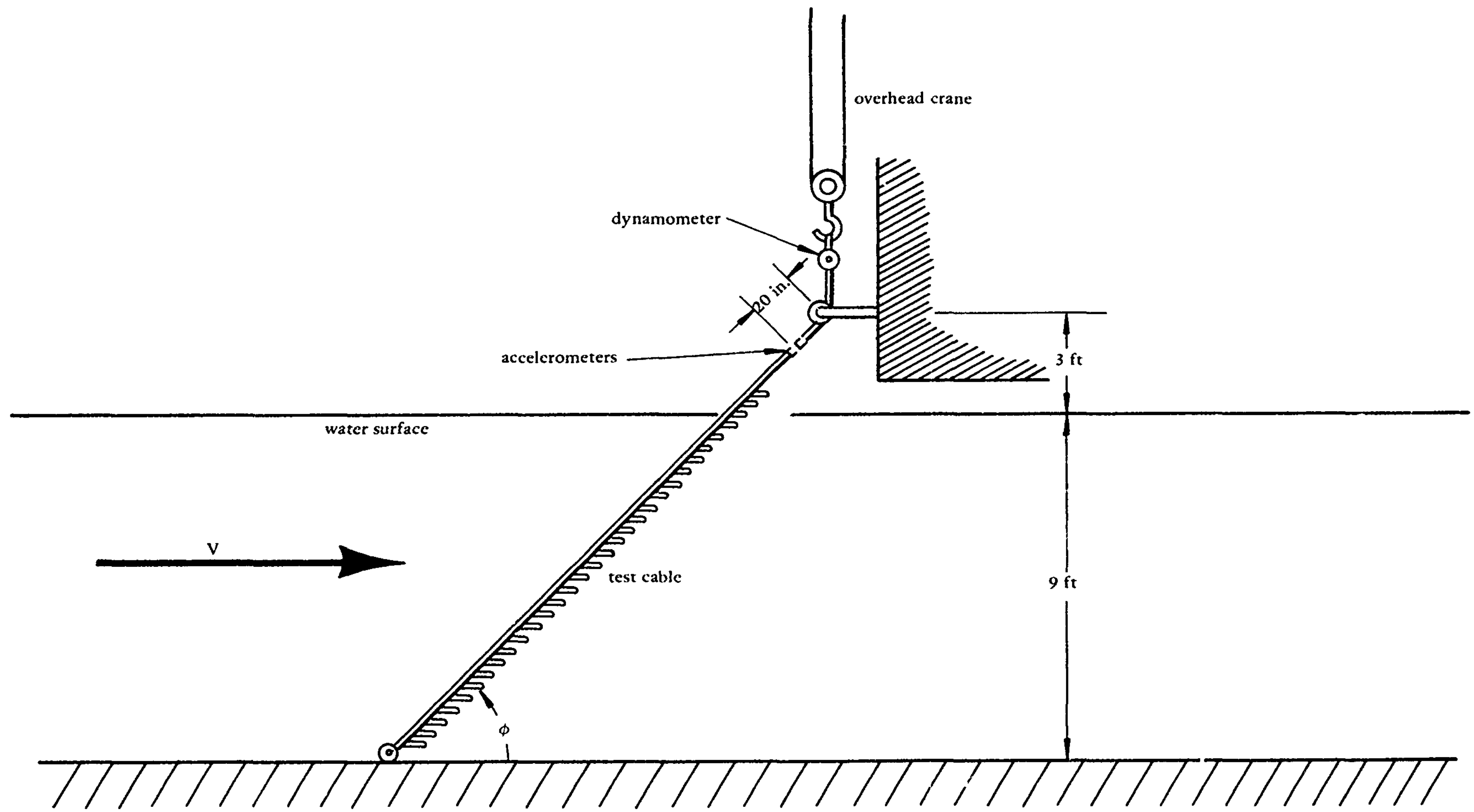


Figure 16. Test arrangement for cable strumming tests. (from Reference 14).

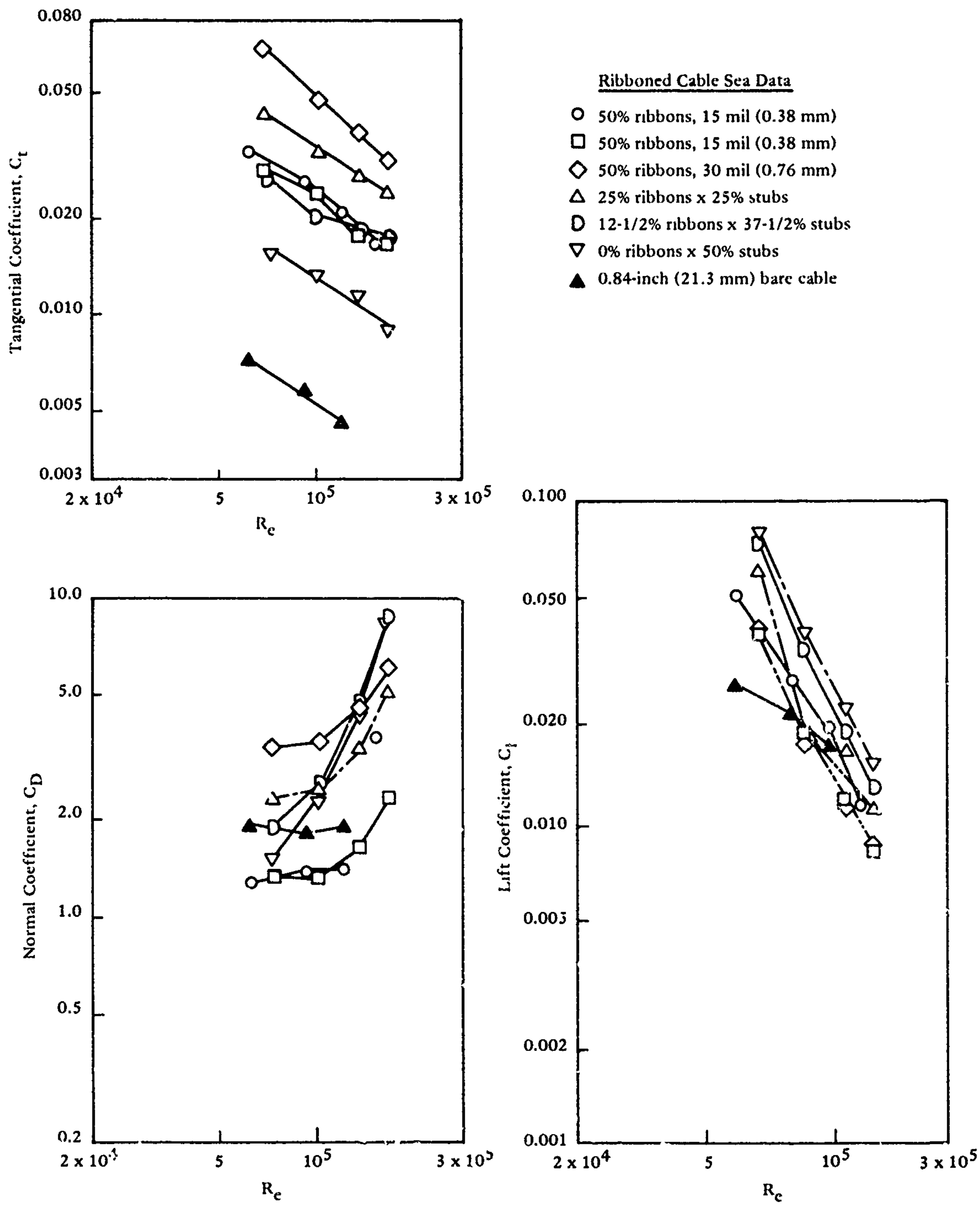
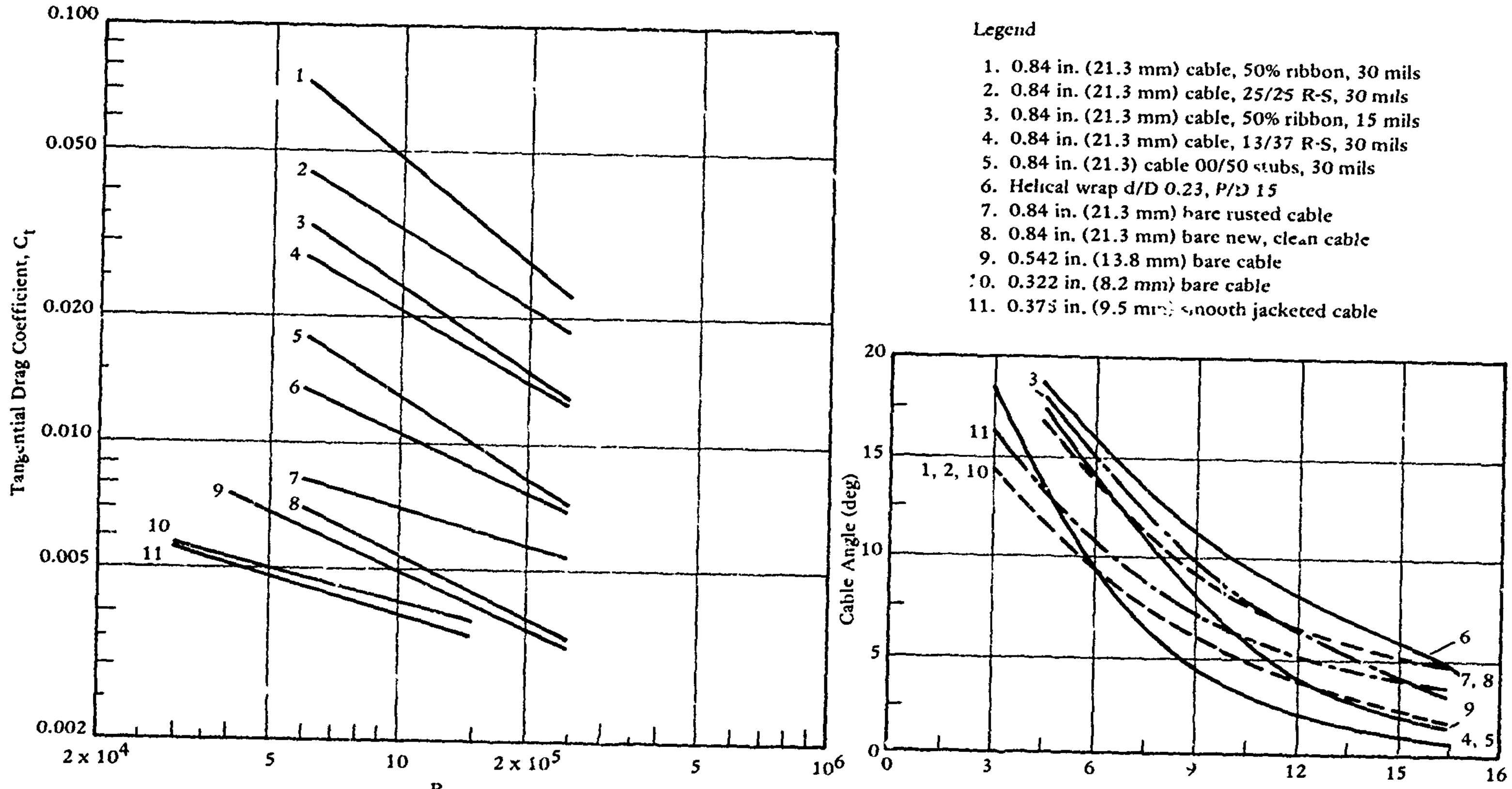


Figure 17. Hydrodynamic drag coefficients for ribbon faired towcables compared to bare cable, DTNSRDC. (from Reference 15).



(a) Tangential drag coefficients.

(b) Towing angles.

Figure 18. Tangential drag coefficients and towing angles for various towed array towcables, DTNSRDC. (from Reference 15).

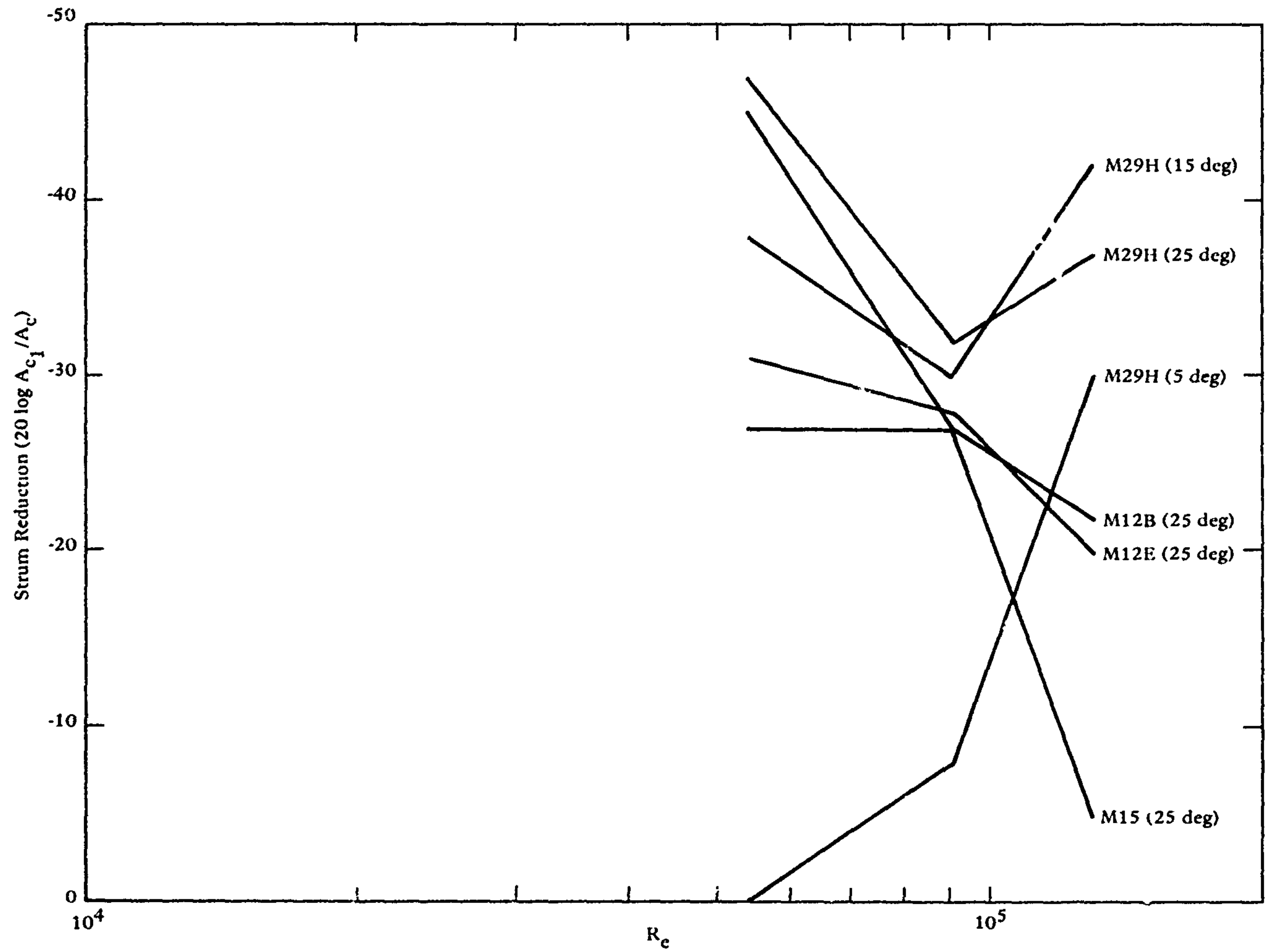


Figure 19. NUC ribbon fairing strumming reduction. (from Reference 12).

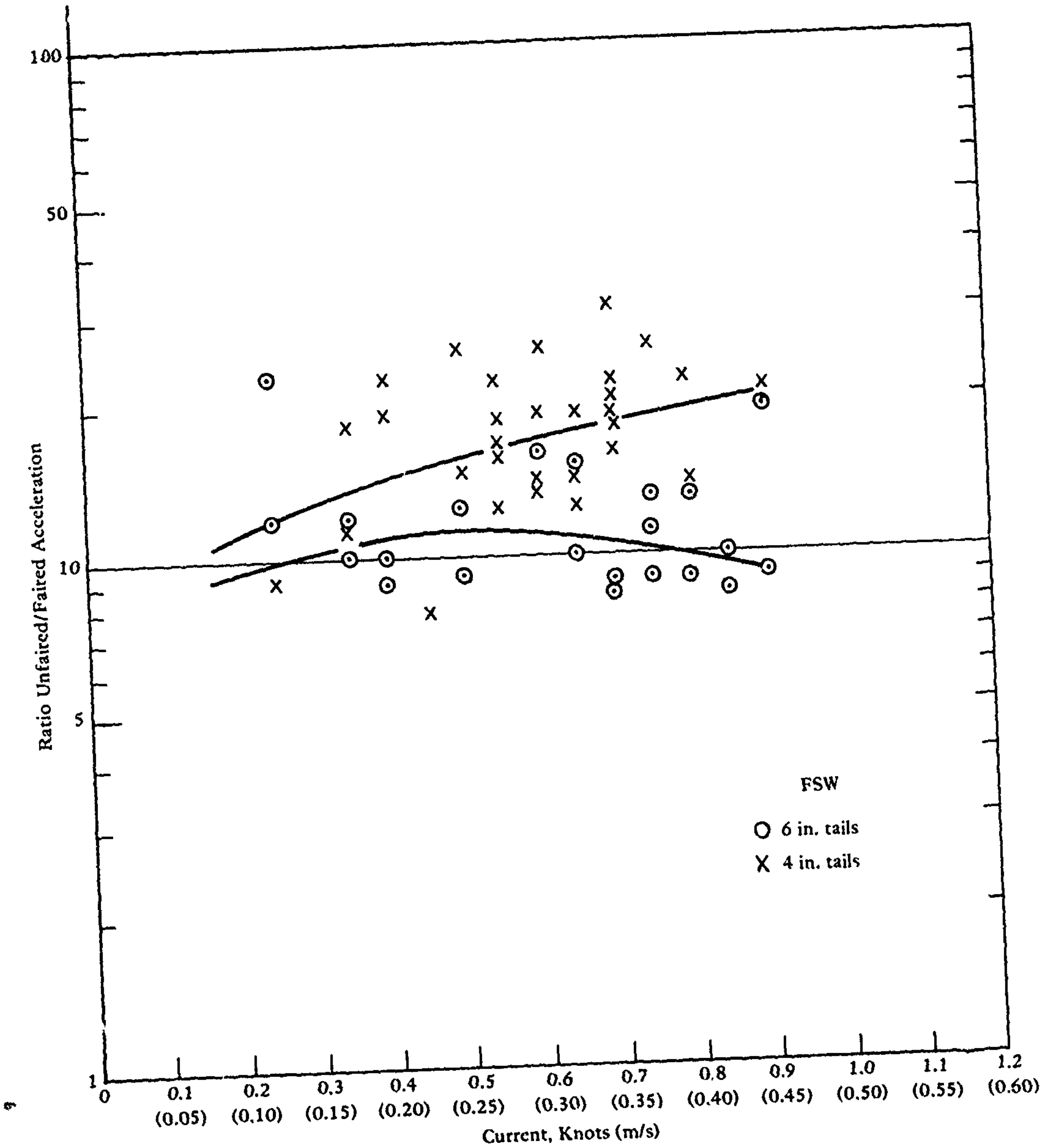


Figure 20. Comparison of accelerations for 4-in. (101.6 mm) and 6-in. (152.4 mm) FSW fairings, WHOI. (from Reference 6).

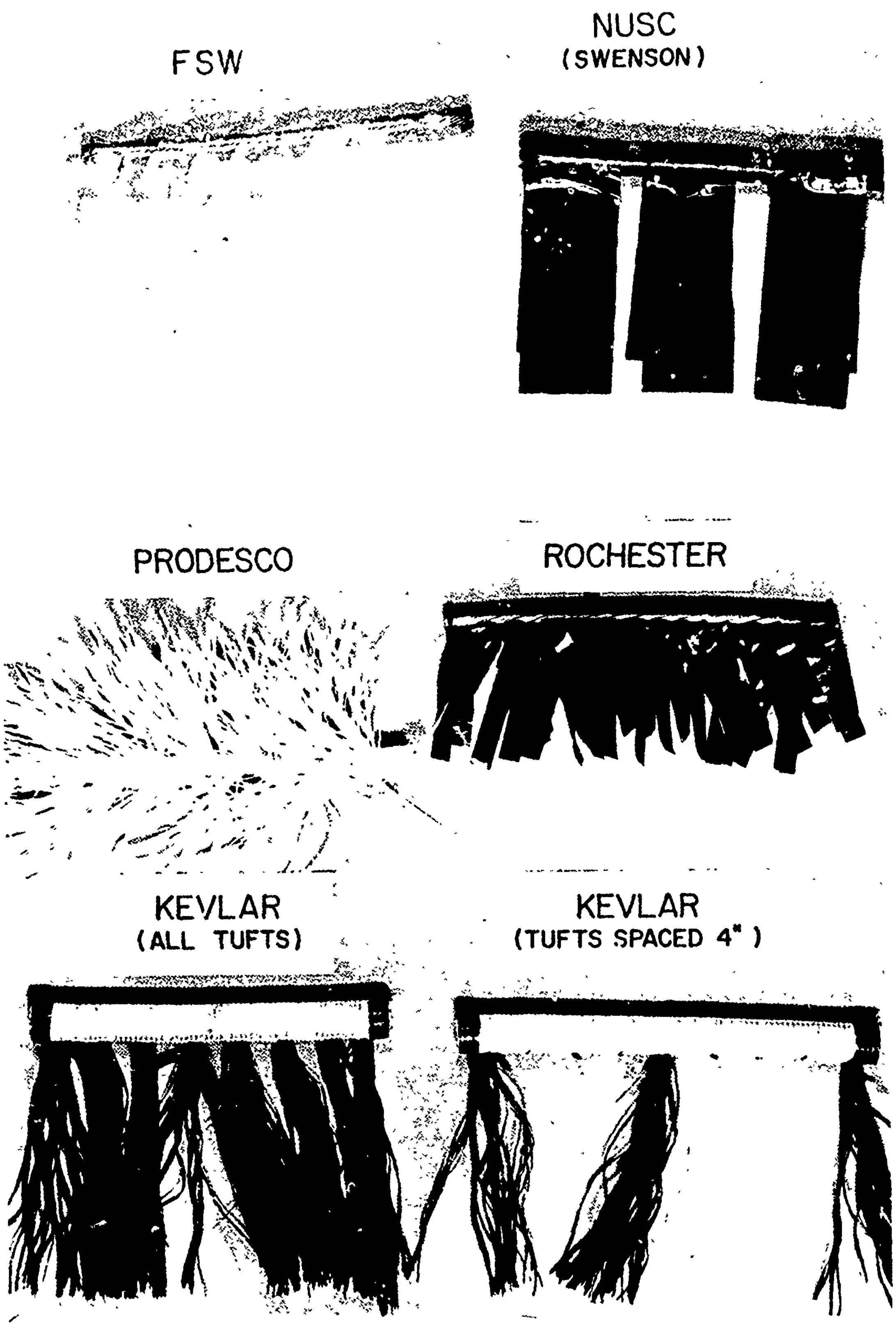
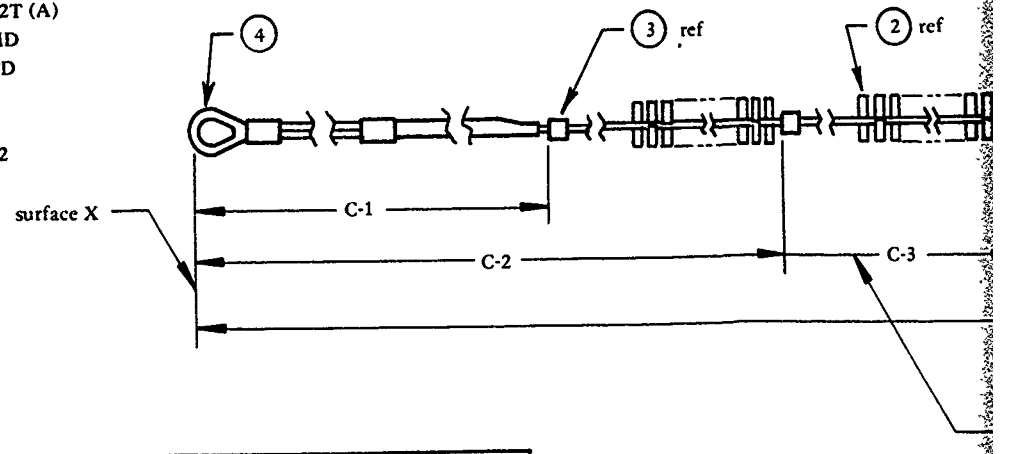


Figure 21. Fairings used in test, WHOI. (from Reference 6).

Notes:

1. Locate (3) using tabulation block dimensions.
2. Permanently tag identify "30003-3010068 – ". Including applicable dwg rev letter, in accordance with MIL-STD-130.
3. Mate (2) with (1) thus:
   - (A) Separate the 12 outer strands of (1) wire from its core without permanent damage.
   - (B) Slide (2) under the open strands of (1). Note – (2) must pass under at least 3 strands of (1) and outside the core of (1). Position (2) approximately as shown.
   - (C) Close the strands of (1) to hold (2) in place.
   - (D) Item (2) to be installed central to item (1) within ±1 inch.
4. Material (2) – polyurethane film having the following physical properties.

		ASTM Test Method
Specific gravity	1.11	D792-64T
Yield, sq in./lb	24,900	
Tensile strength	6,000 psi	D882-61T MD
	3,000 psi	TD
Elongation at break, %	350	D882-61T MD
	650	TD
Impact strength, grams	390	D1709-62T (A)
Tear strength, lb/in.	250	D1004 MD
	380	TD
Moisture vapc nsmission, GM/MIL/100 sq in./24 hr	70	E-96-E
Low temperature, deg F	–100	D1790-62



Tab of (3) Locations	
No.	"C" ft ± 0.5 ft
1	2
2	5
3	15
4	30
5	45
6	60
7	80
8	100
9	120

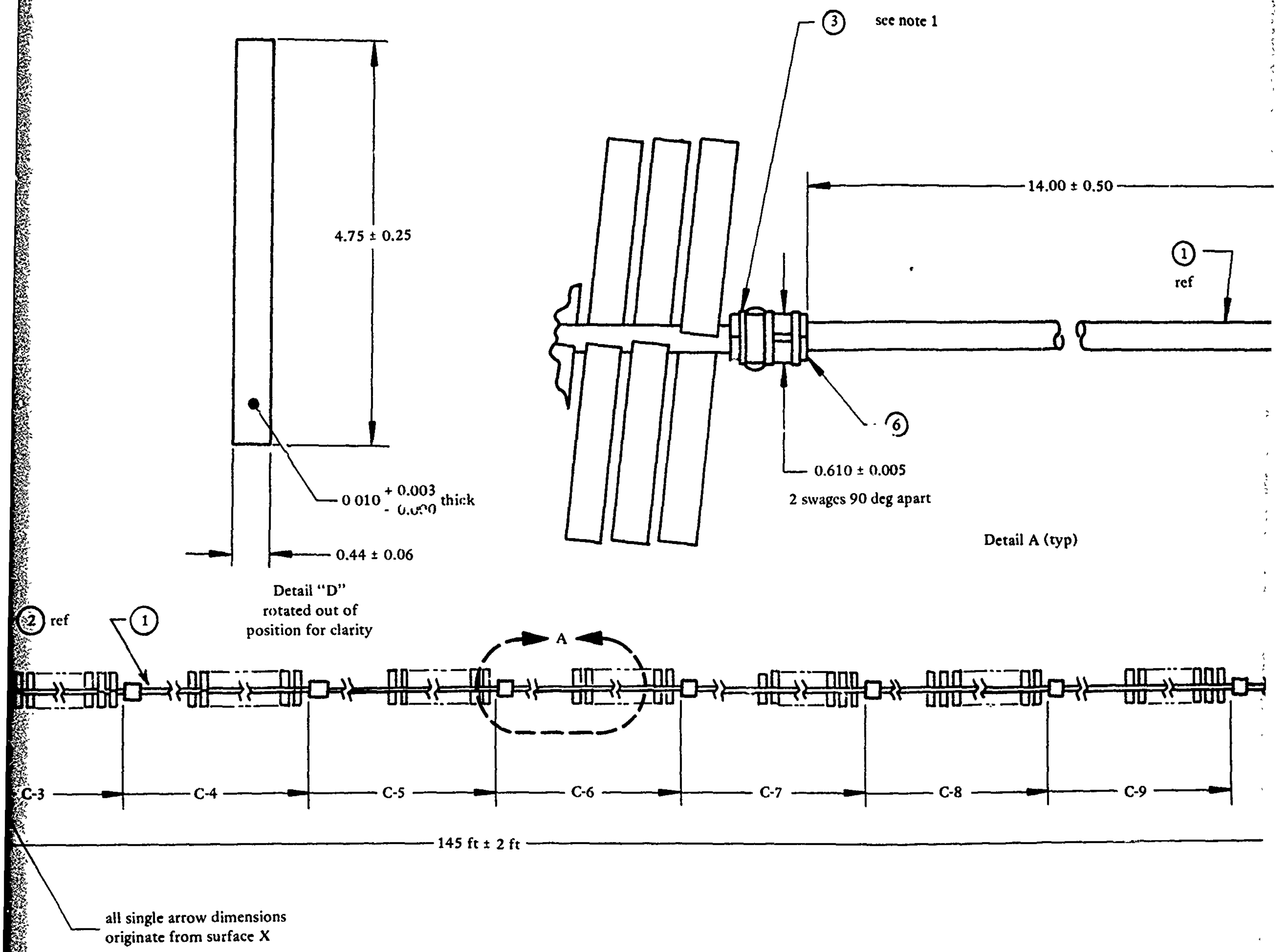
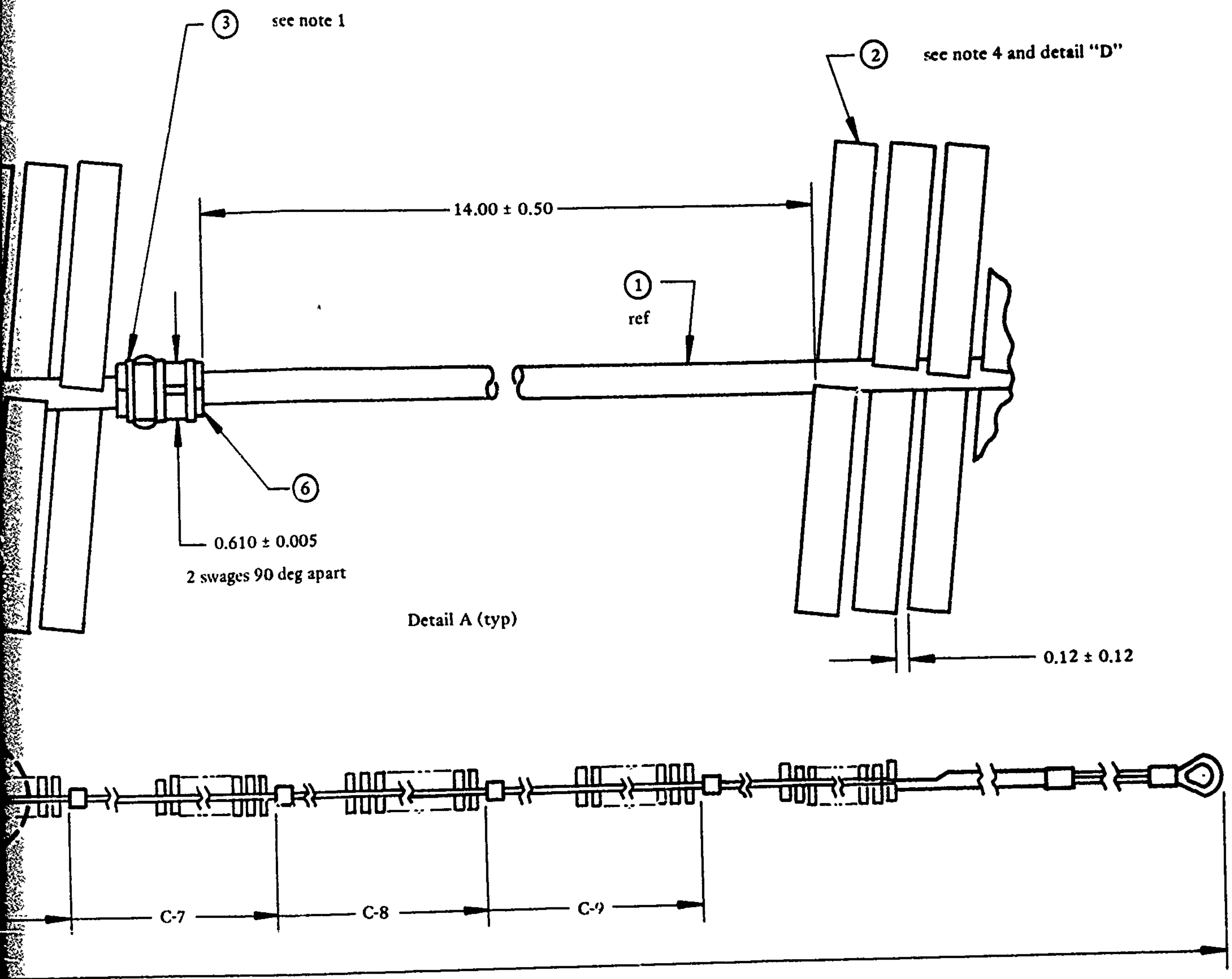


Figure 22. NCSL sweep wire ribbon fairing.

2



3
see note 1
2
see note 4 and detail "D"
14.00 ± 0.50
1
ref
6
0.610 ± 0.005
2 swages 90 deg apart
Detail A (typ)
0.12 ± 0.12
C-7
C-8
C-9

3

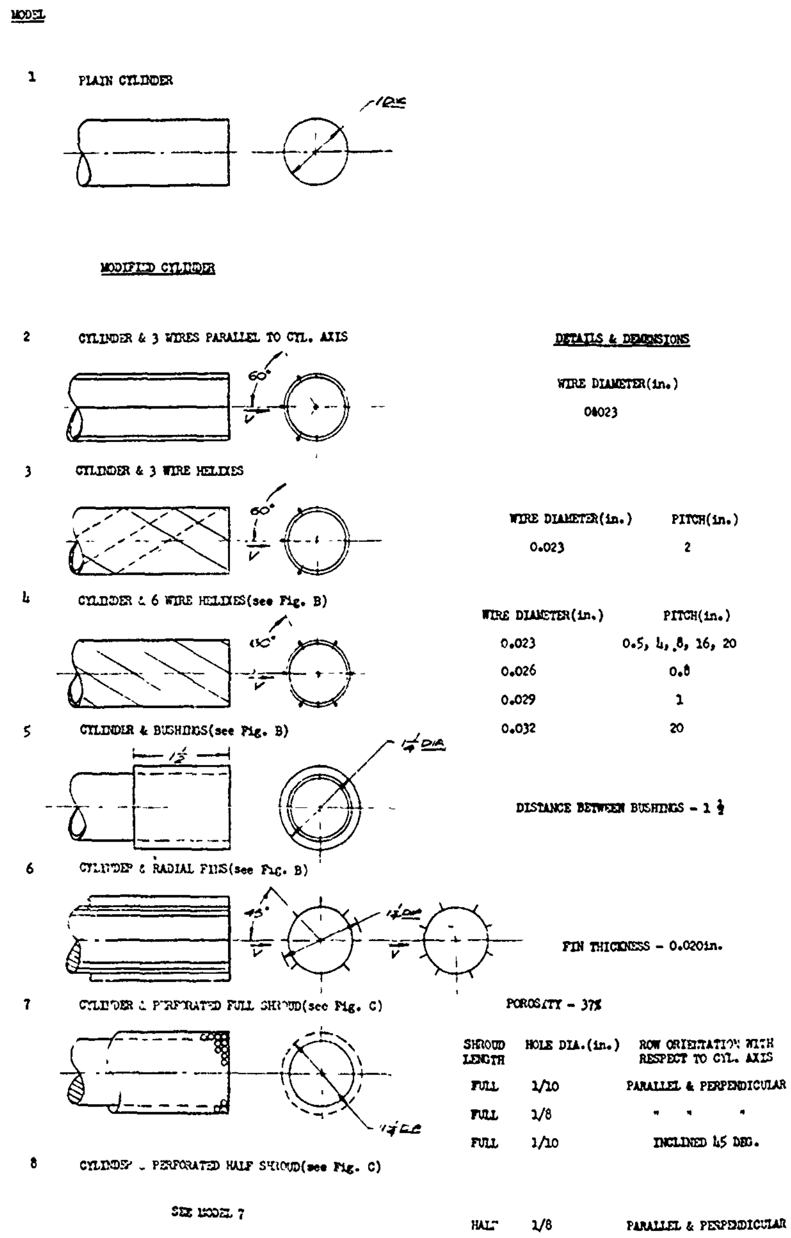


Figure 23. Water channel models. (from Reference 17: "Suppression of the fluid-induced vibration of circular cylinders," by P. Price and R. W. Thompson, in Journal of the Engineering Mechanics Division American Society of Civil Engineers, vol. 82, no. EM3, Jul 1956, pp 1030-6).

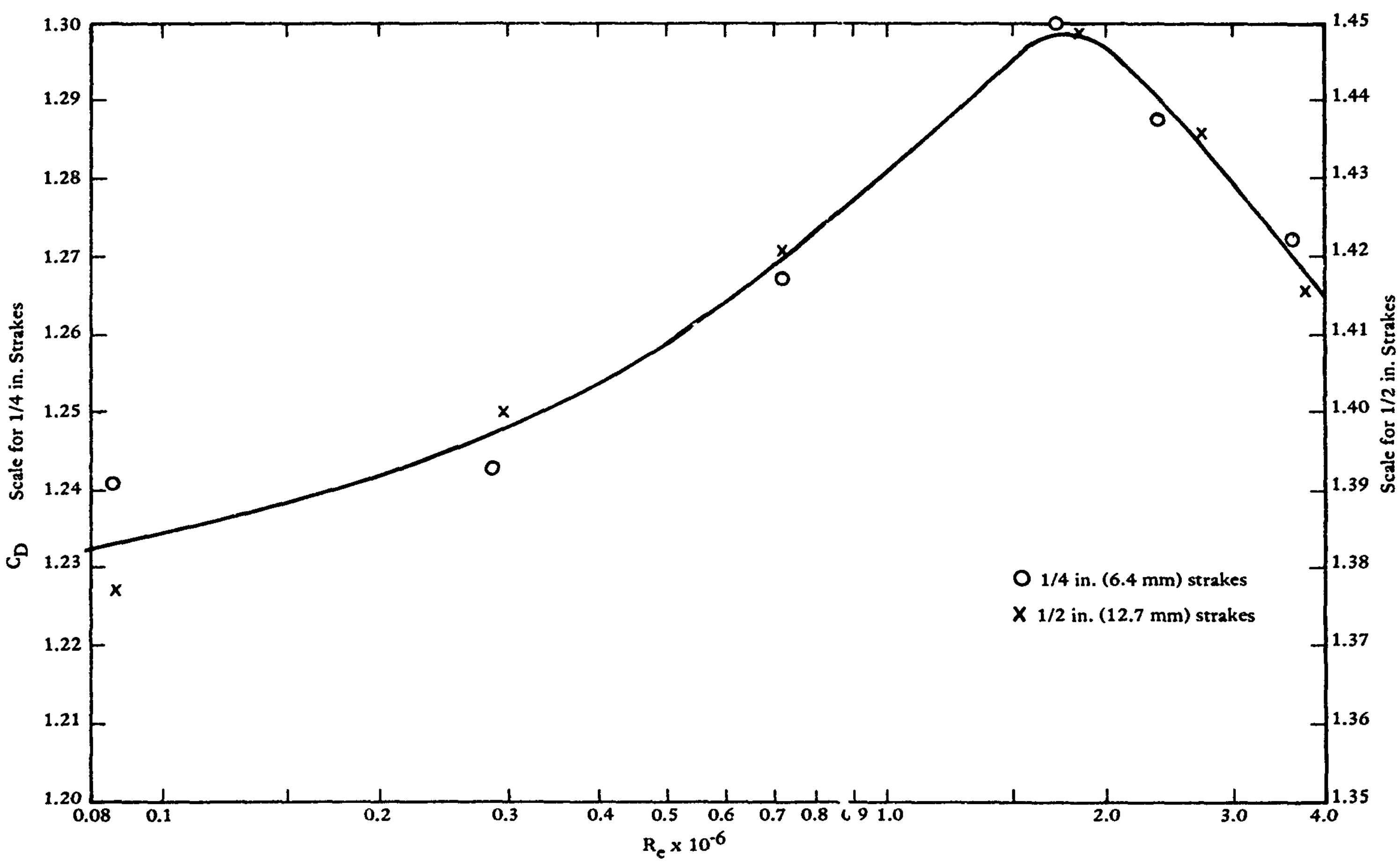


Figure 24. Drag coefficient of a circular cylinder with three helical ridges, NPL. (from Reference 18).

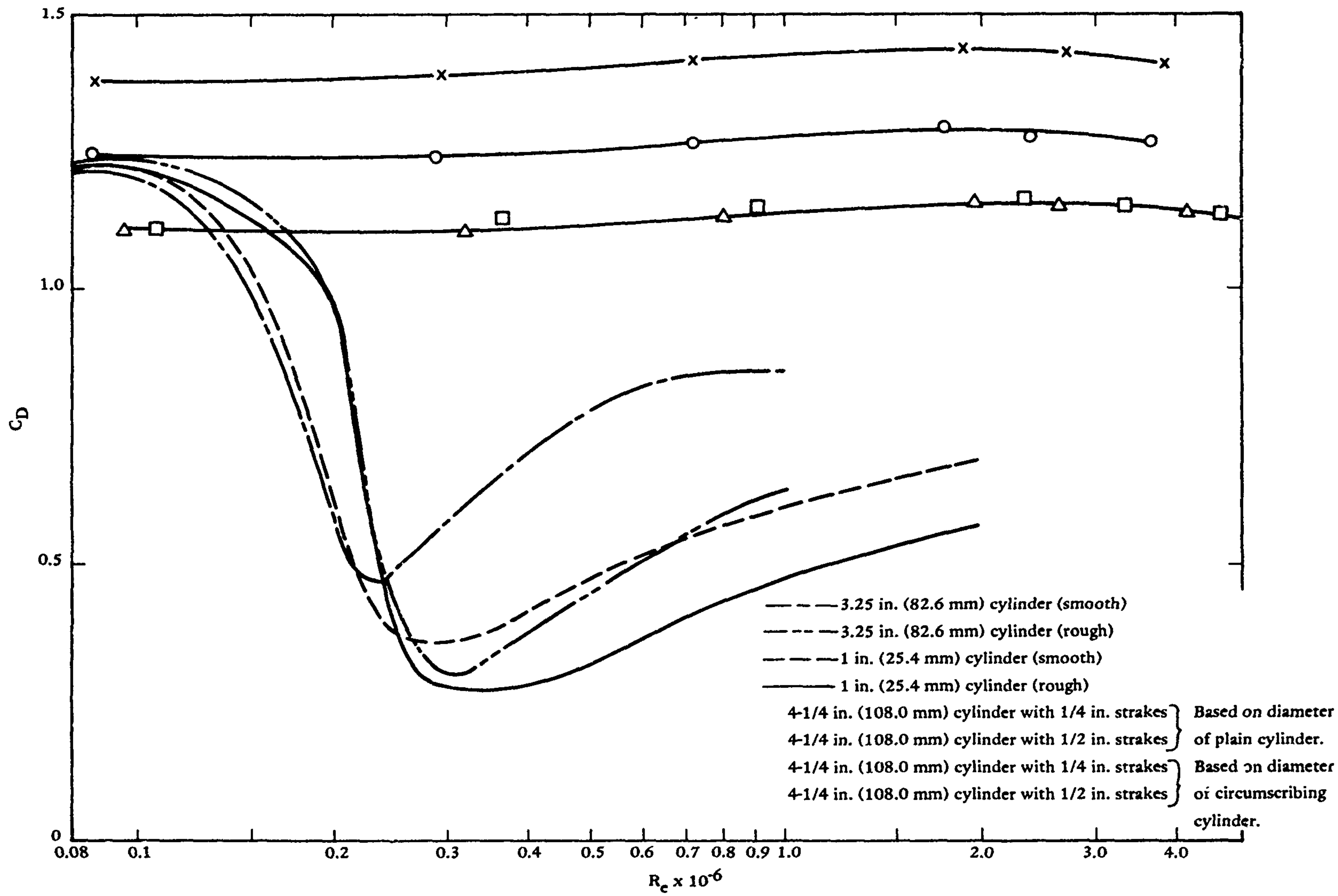


Figure 25. Drag coefficient of a circular cylinder with and without helical ridges, NPL. (from Reference 18).

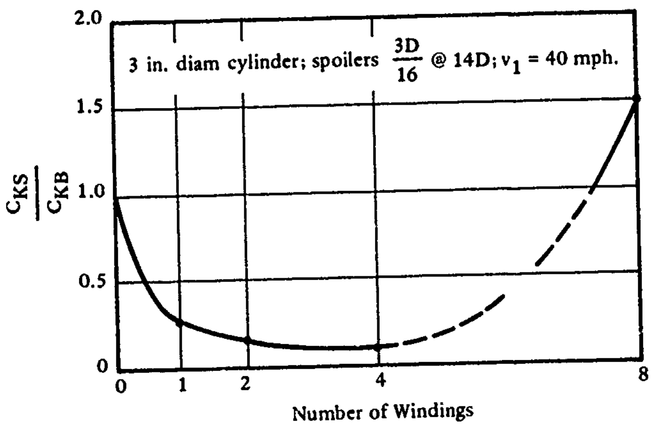


Figure 26. Influence of number of windings on spoiler effectiveness. (from Reference 25): (from "Wind-induced vibrations in antenna members," by W. Weaver, in Journal of Engineering Mechanics, American Society of Civil Engineers, vol 87, no. EM1, Feb 1961, p 158).

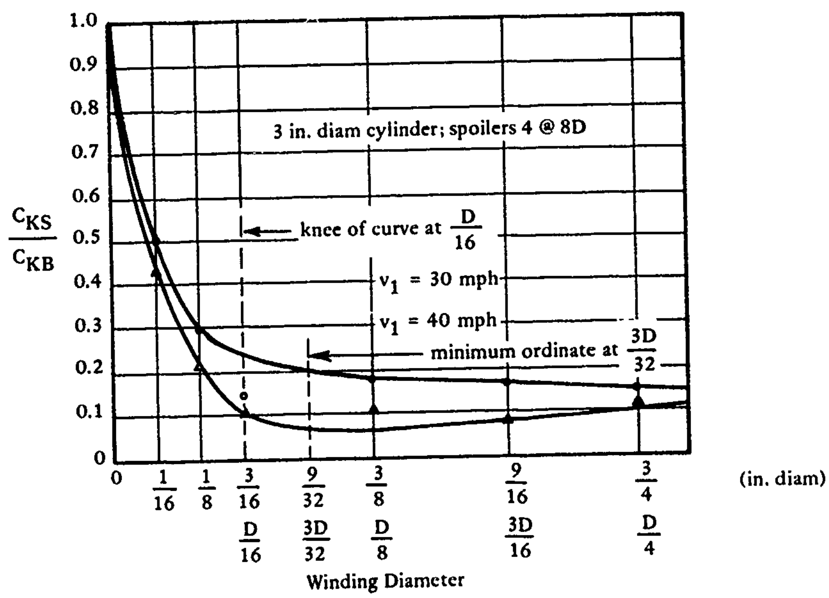


Figure 27. Influence of winding diameter on spoiler effectiveness. (from Reference 25): (from "Wind-induced vibrations in antenna members," by W. Weaver, in Journal of Engineering Mechanics, American Society of Civil Engineers, vol 87, no. EM1, Feb 1961, p 159).

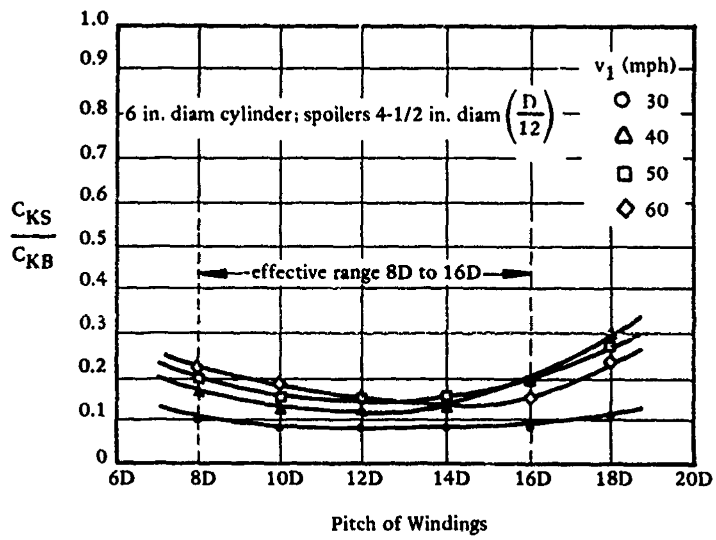


Figure 28. Influence of pitch on spoiler effectiveness. (from Reference 25): (from "Wind-induced vibrations in antenna members," by W. Weaver, in Journal of Engineering Mechanics, American Society of Civil Engineers, vol 87, no. EM1, Feb 1961, p 159).

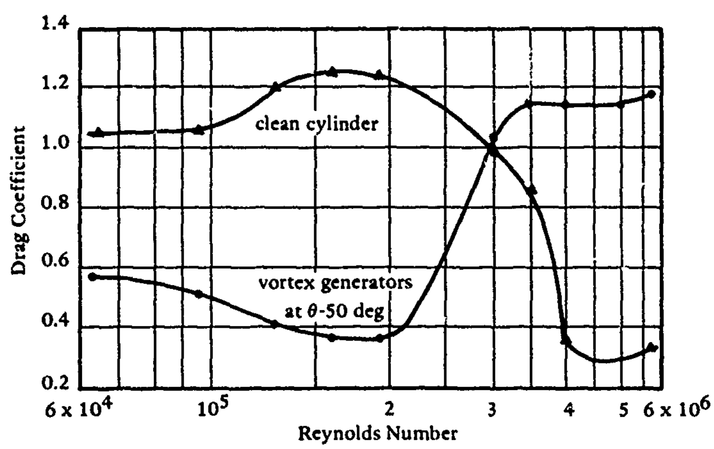
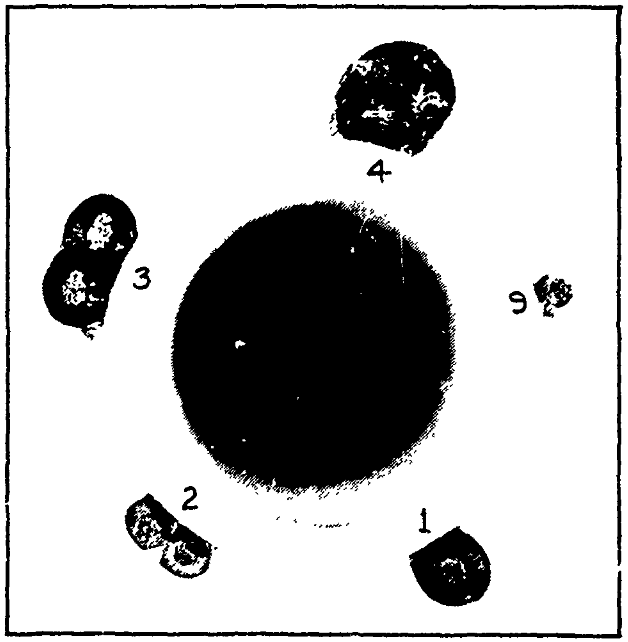
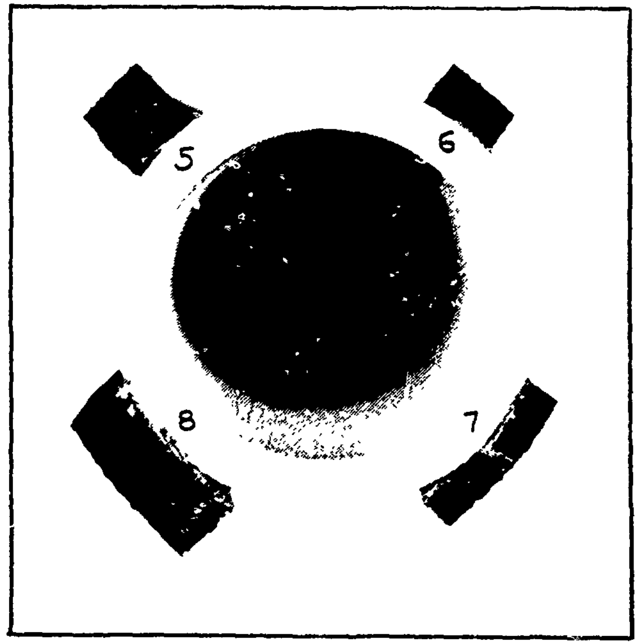


Figure 29. Drag coefficient for cylinder with and without vortex generators. (from Reference 26).

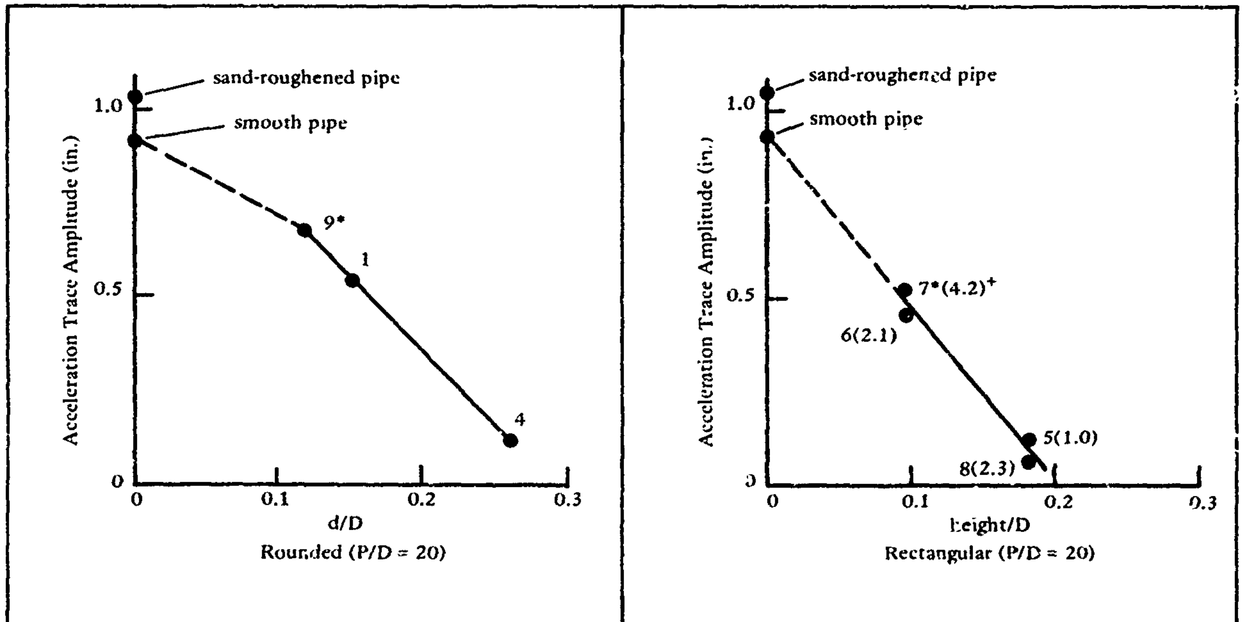


(a) Rounded ridges.



(b) Rectangular ridges.

Figure 30. End views of ridges mounted on pieces of test pipe. (from Reference 28).



*Ridge type. +Ridge width-to-height ratio.

Figure 31. Dependence on ridge height ratio of transverse vibration, as indicated by accelerometer trace maximum peak-to-peak amplitude for V $\leq$ 6 fps (1.8 m/s)(from Reference 26).

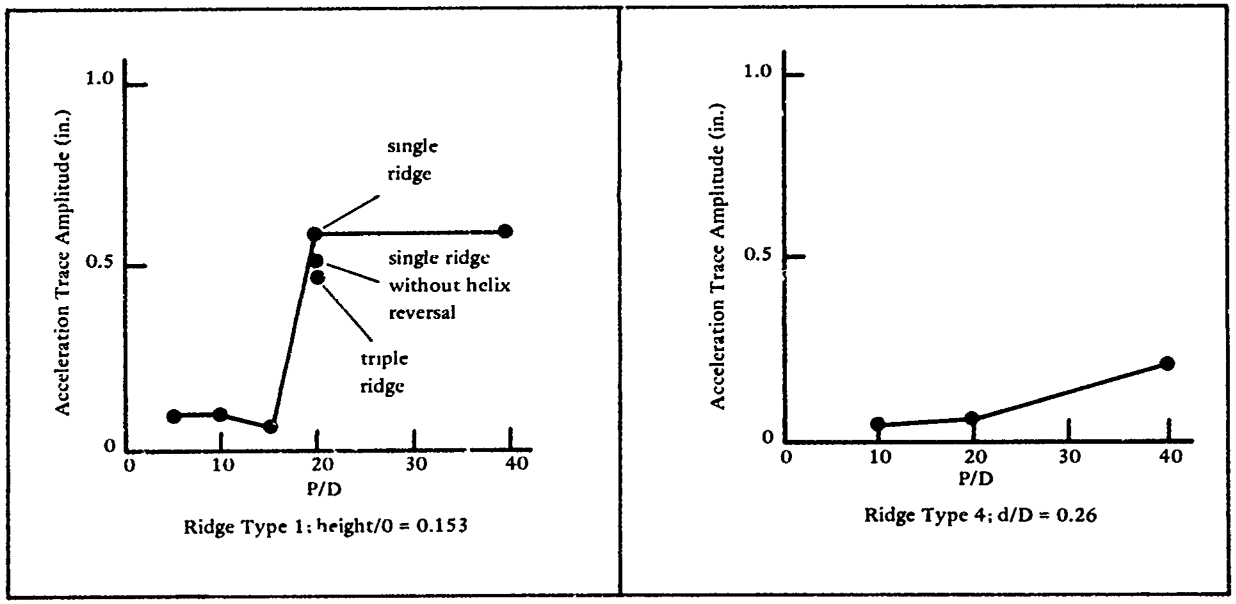


Figure 32. Dependence on ridge pitch ratio of transverse vibration, as indicated by accelerometer trace maximum peak-to-peak amplitude for V $\leq$ 6 fps (1.8 m/s)(from Reference 26).

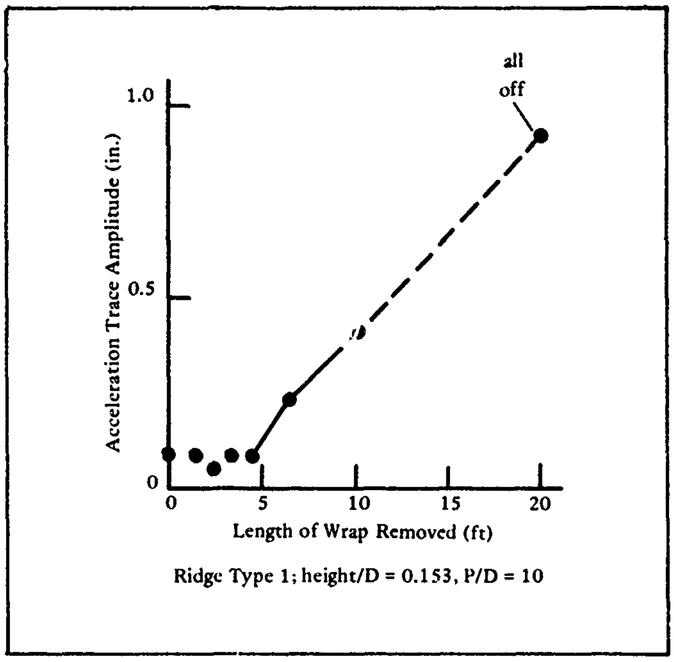


Figure 33. Dependence on ridge removal of transverse vibration, as indicated by accelerometer trace maximum peak-to-peak amplitude for V $\leq$ 6 fps (1.8 m/s) (from Reference 26).

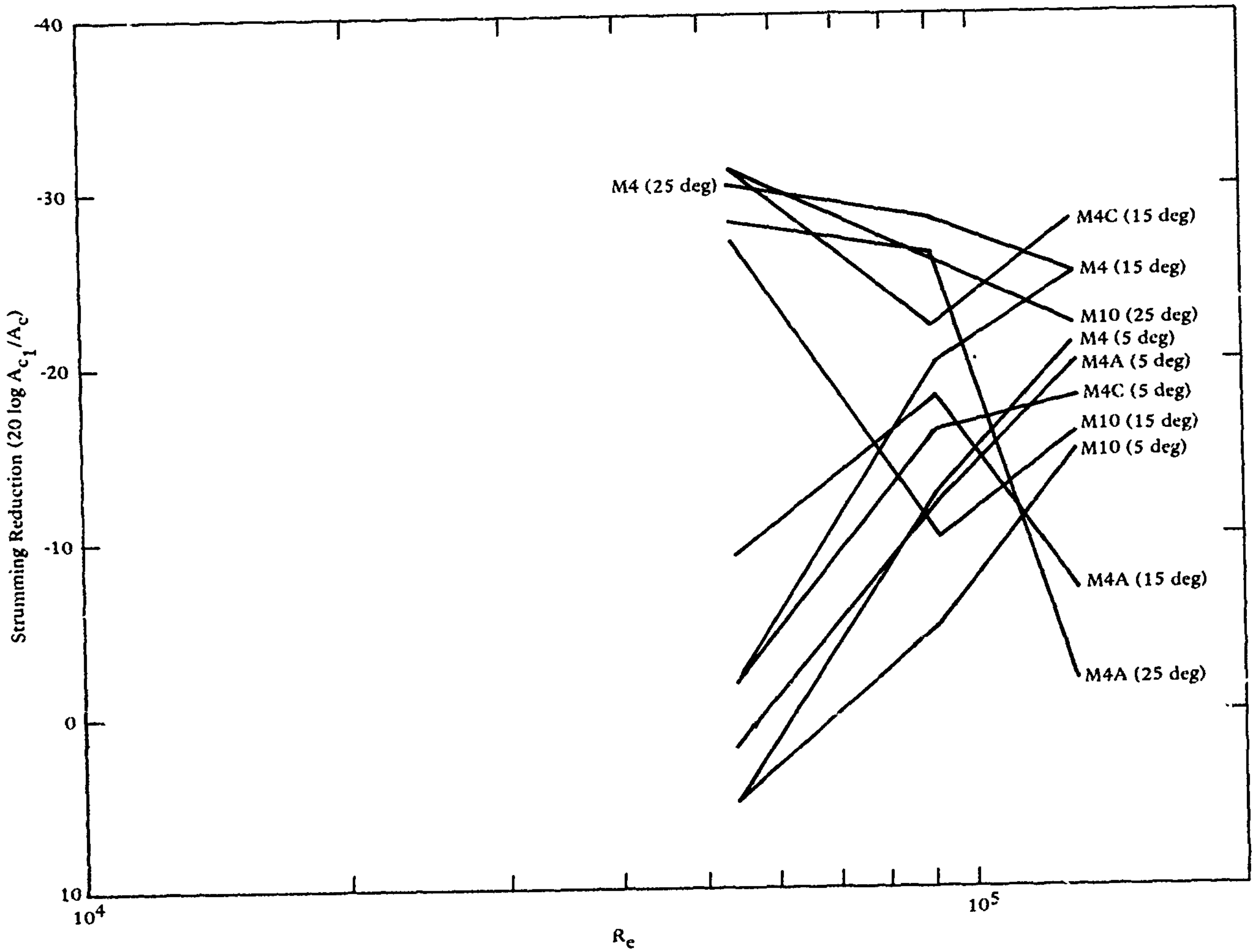


Figure 34. NUC helical ridge.

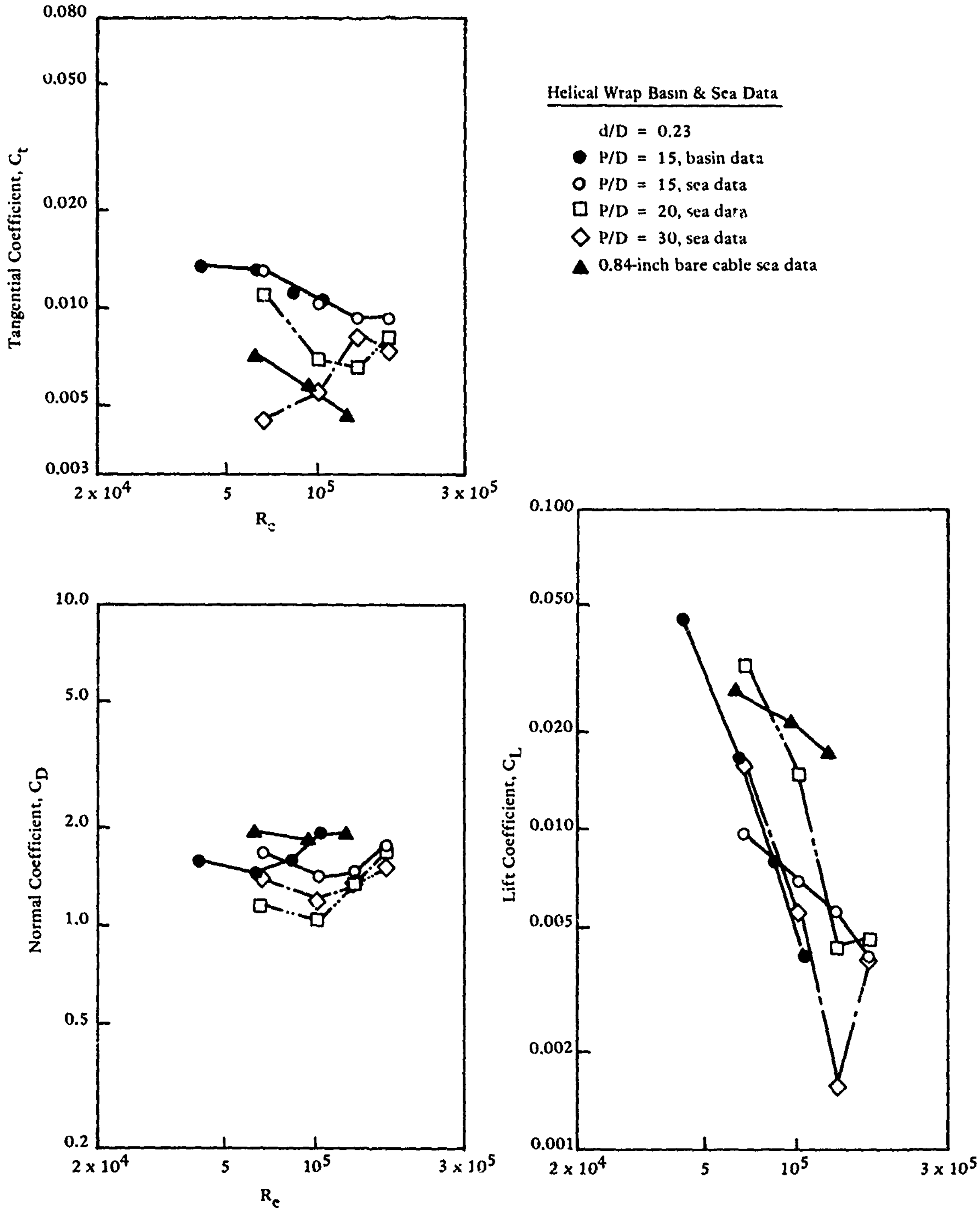


Figure 55. Hydrodynamic drag coefficients for helically wrapped cables compared to bare cable, DTNSRDC. (from Reference 15).

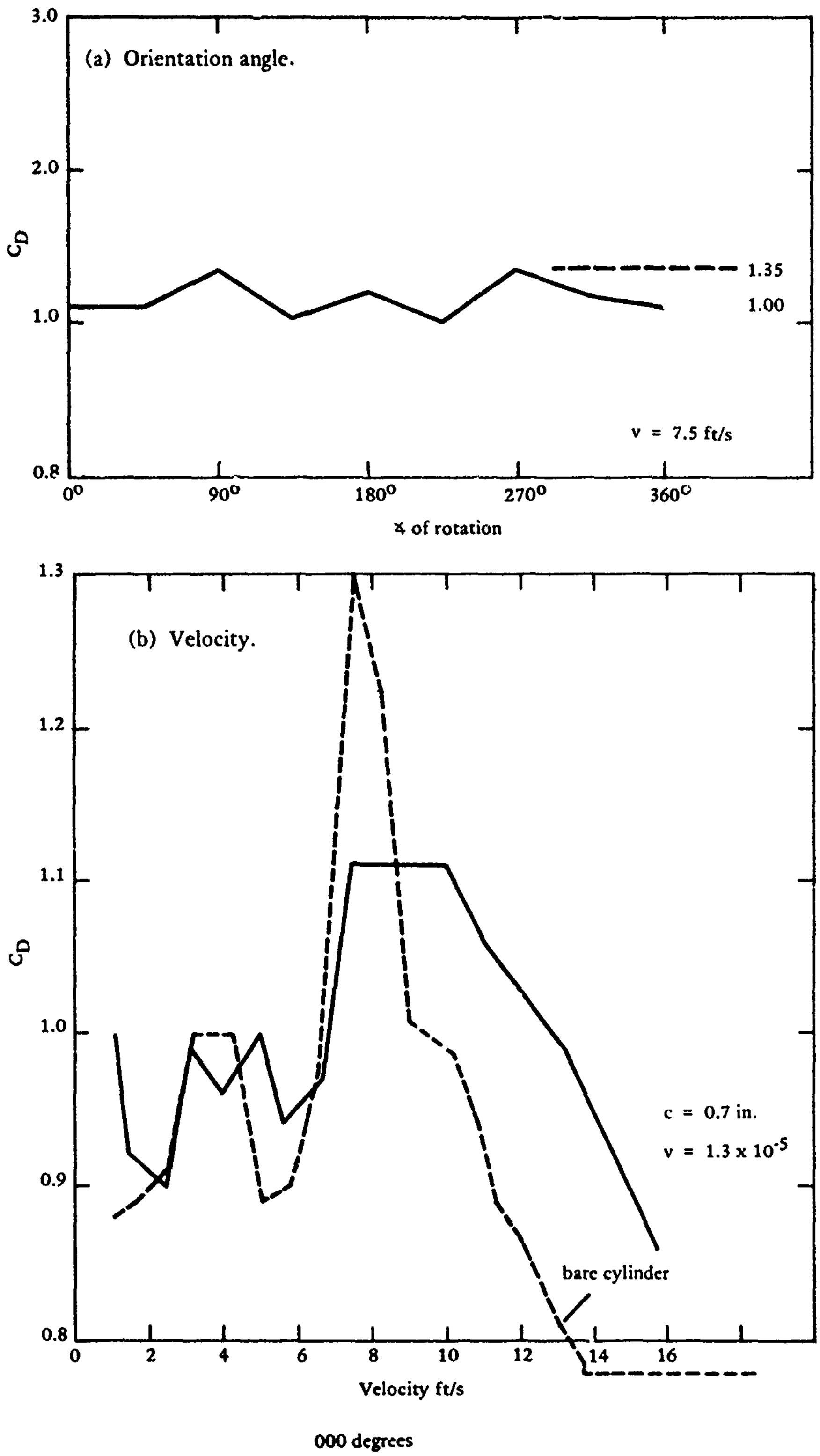


Figure 36. Drag coefficient as a function of velocity and orientation angle. (from Reference 7).

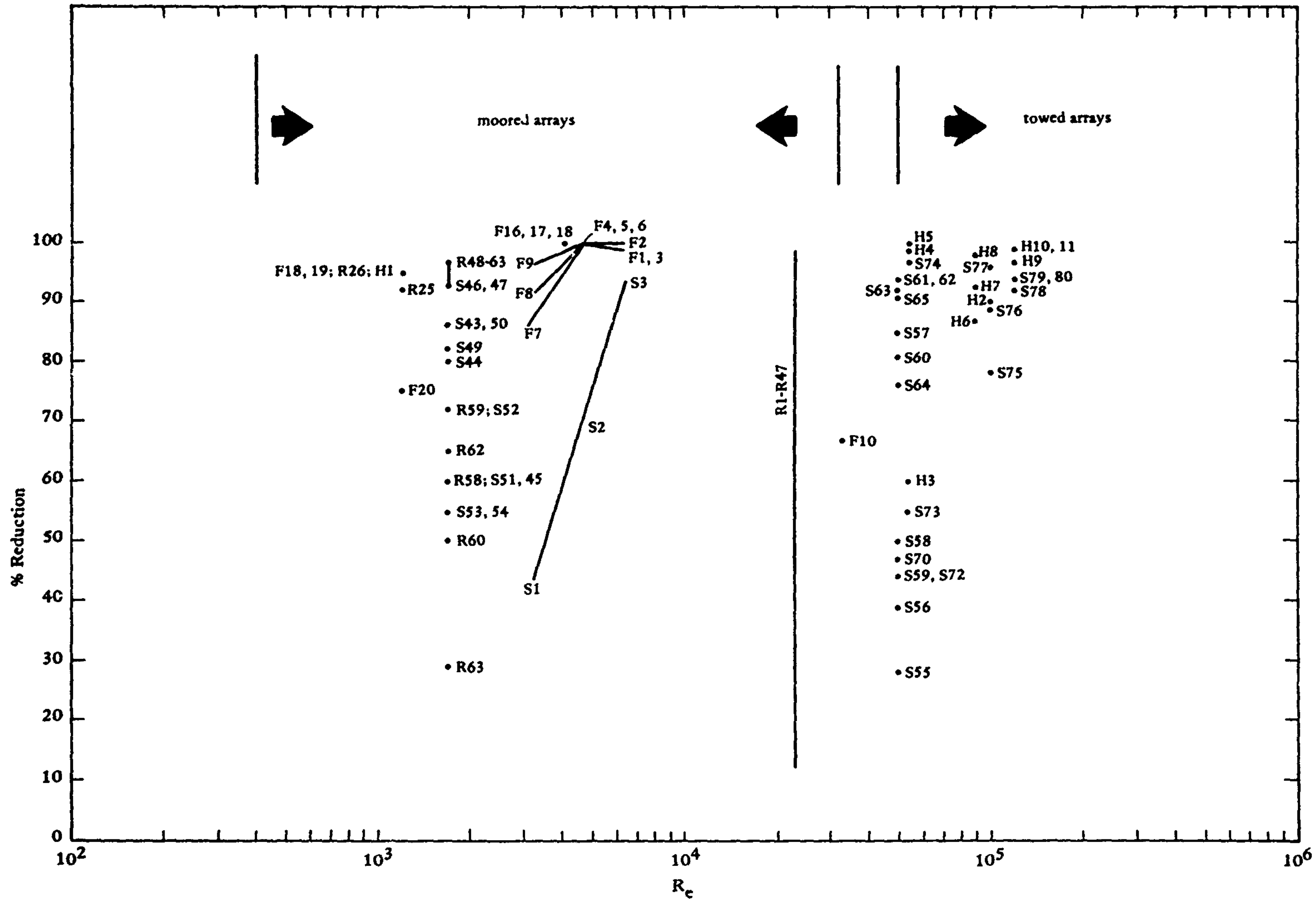


Figure 37. Percent reduction in strumming acceleration with respect to a bare cable (all angles of flow). (see Tables 22-25 for symbols).

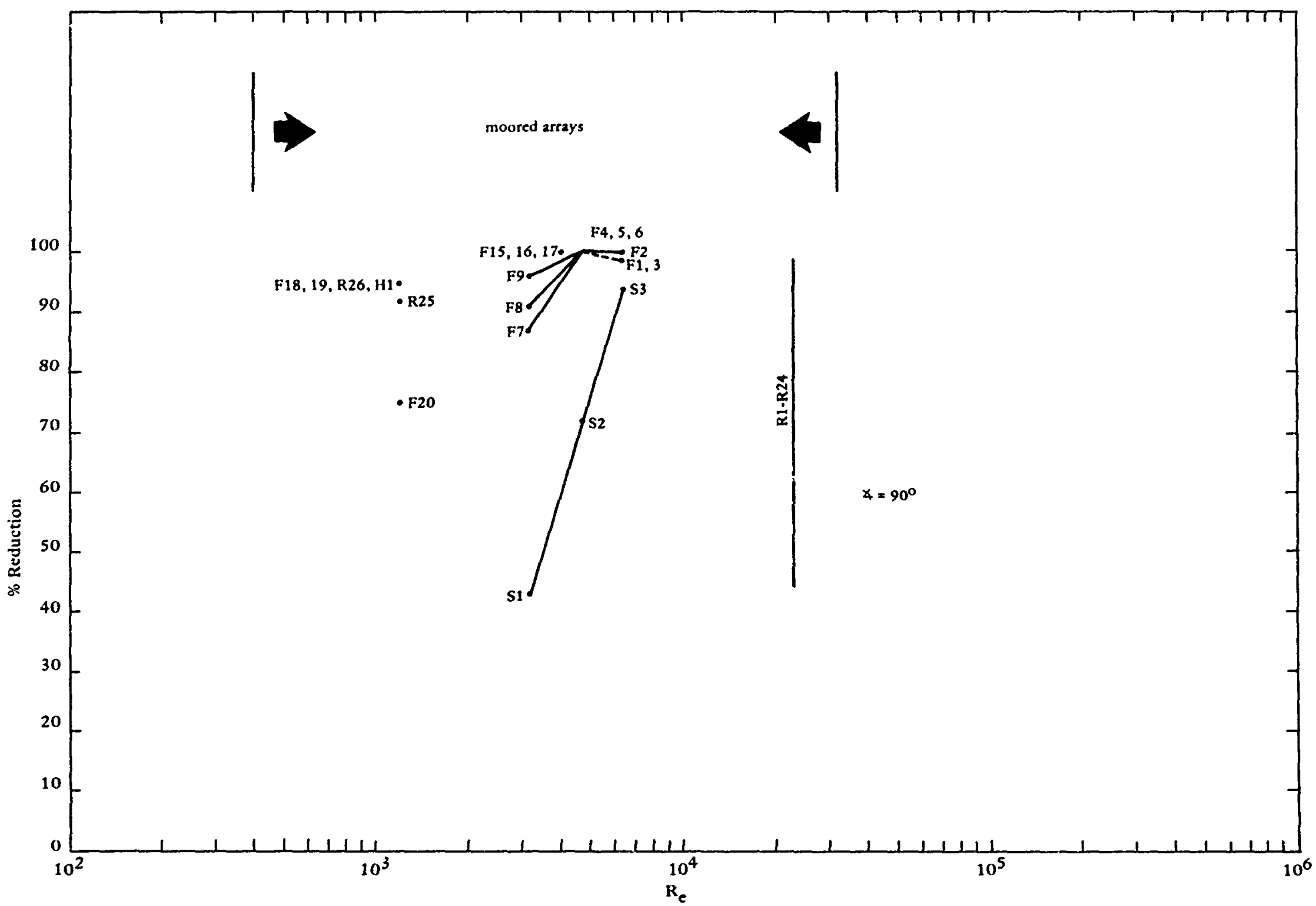
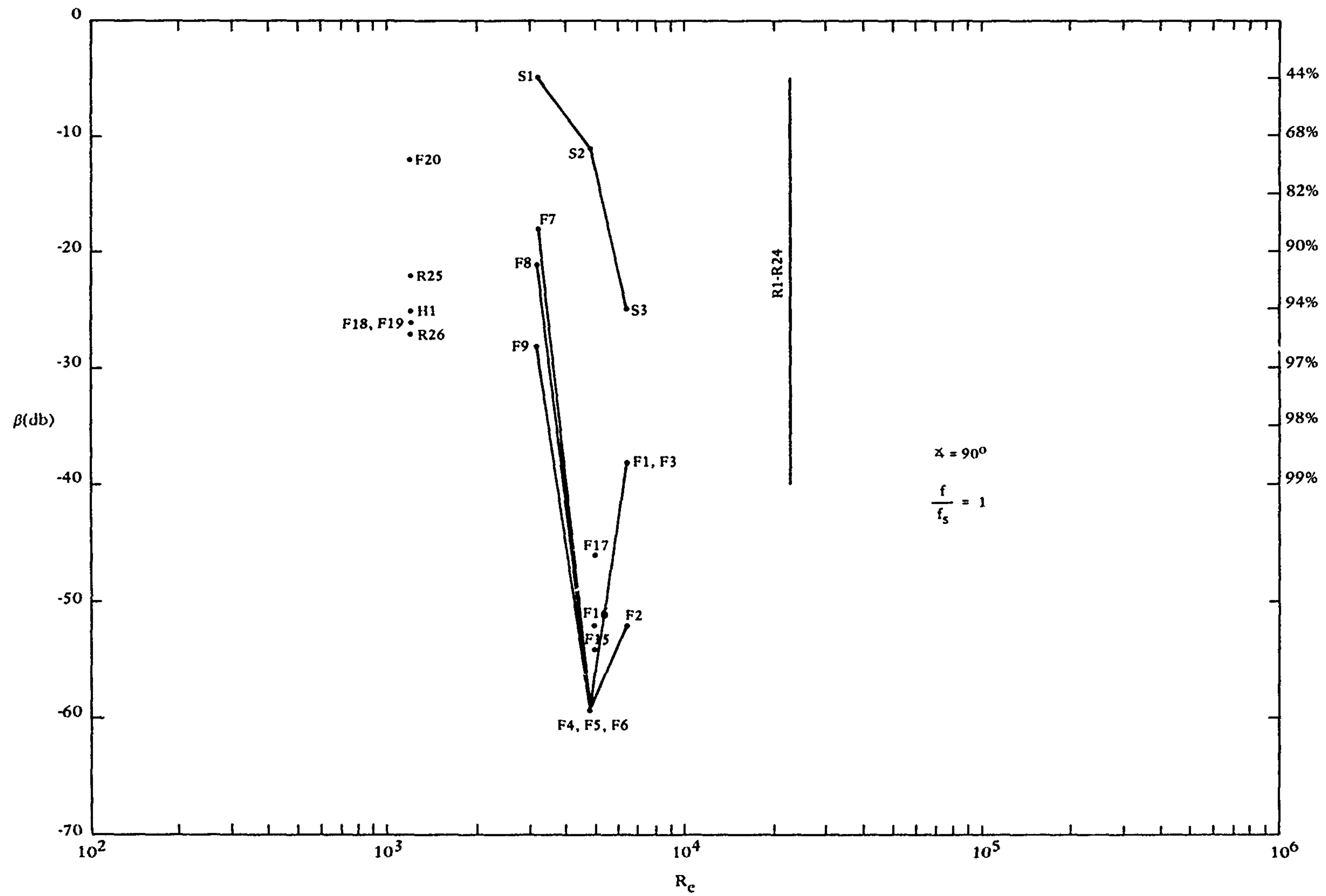


Figure 38. Percent reduction in strumming acceleration with respect to a bare cable. (see Tables 22-25 for symbols).



Figurc 39. Strumming reduction in decibels. (see Tables 22-25 for symbols).

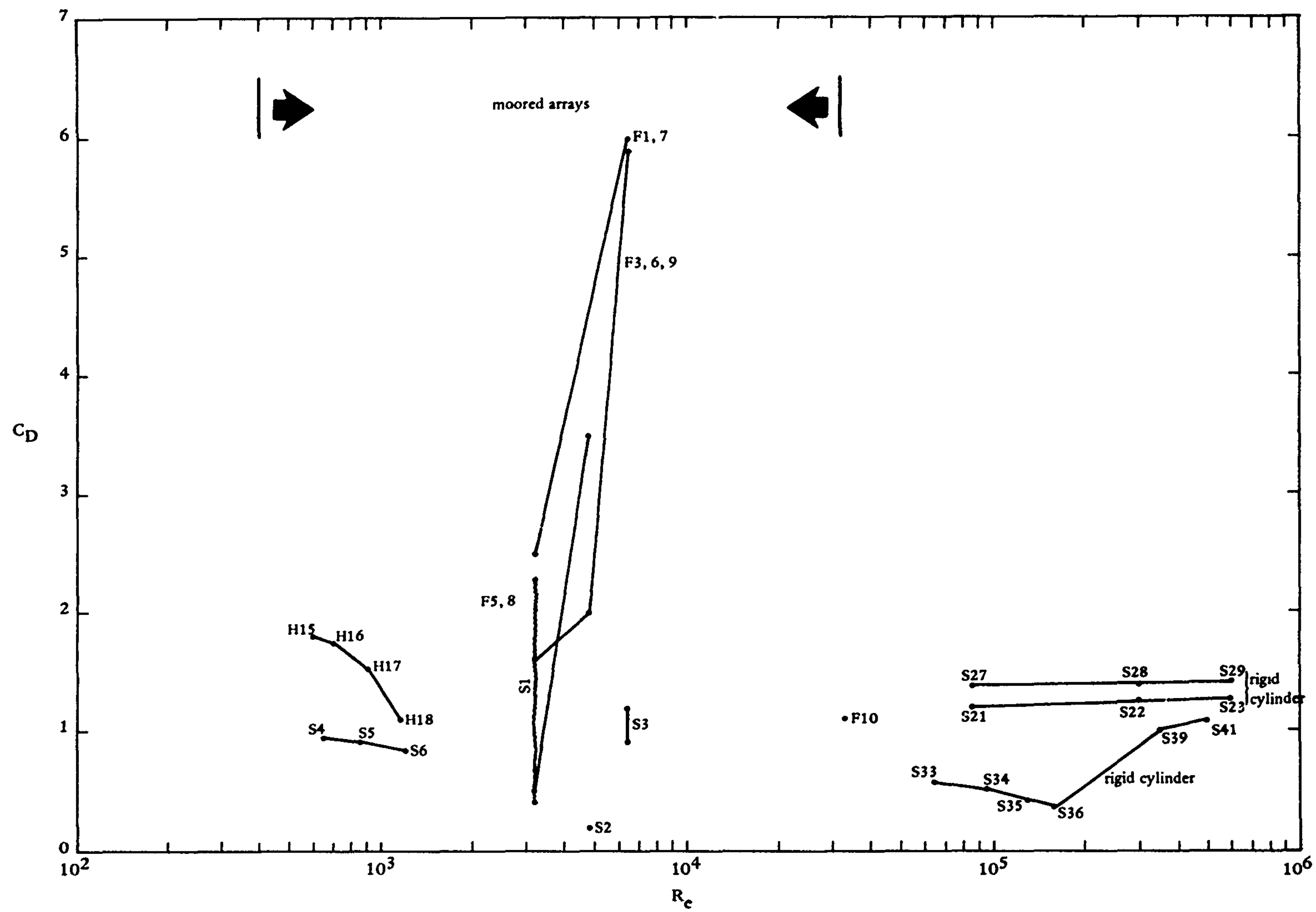


Figure 40. Drag coefficient at an orientation angle of 90 degrees. (see Tables 22-25 for symbols).

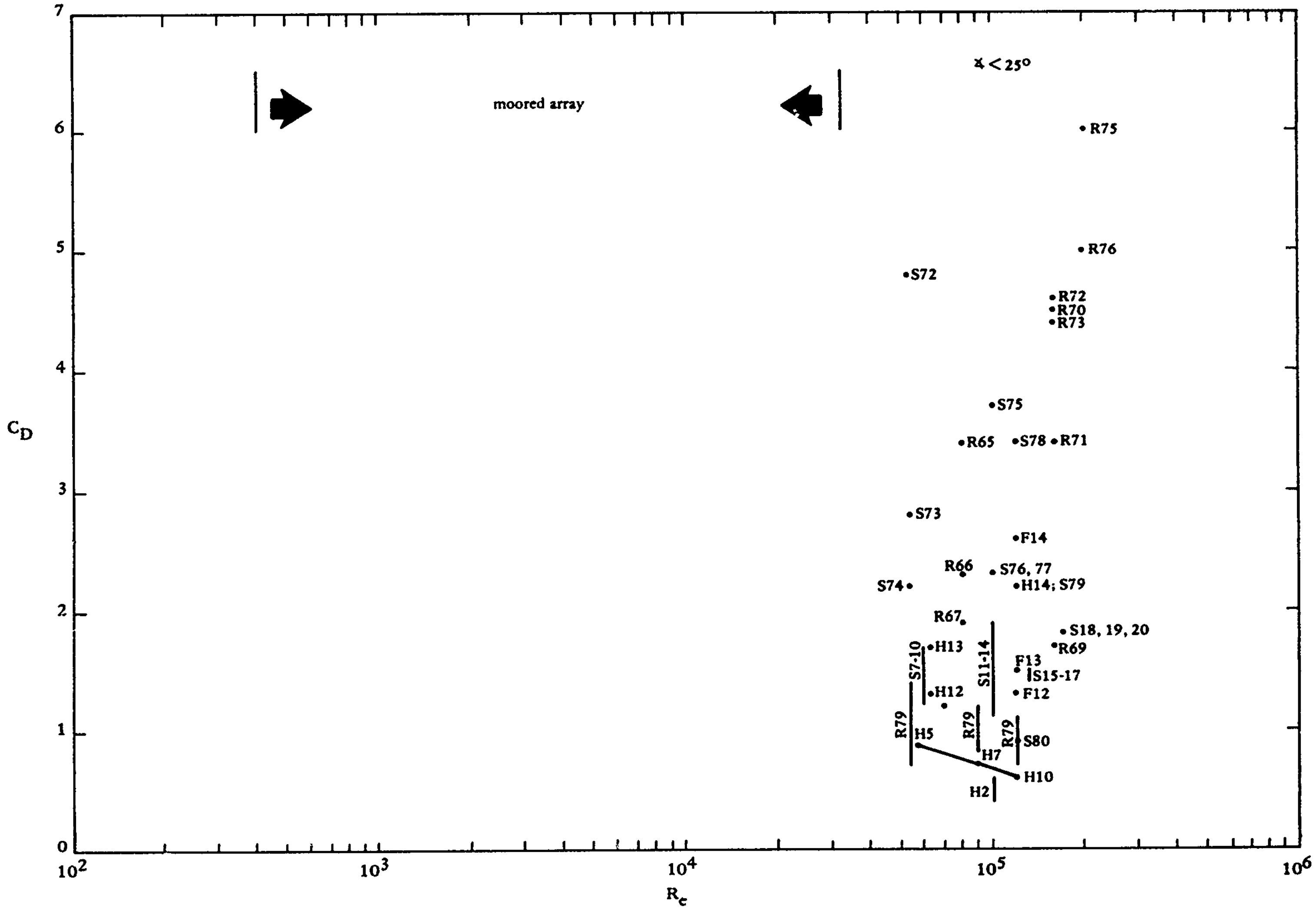


Figure 41. Drag coefficient at an orientation angle < 25 degrees. (see Tables 22-25 for symbols).

Table 1. Physical Parameters for Strumming Suppression Devices.

Type of Device	Geometric & Material Parameters

Fringe	Type of Material
	Density of Coverage
	Length
	Spacing
	Geometry
	    Trailing
	    Helical

Hair	Type of Material Density of Coverage Length

Ribbon	Type of Material
	Length
	Width
	Spacing
	Geometry
	    Trailing
	    Helical

Helical Ridge	Geometry
	    Round
	    Rectangular
	Diameter or Height Relative to Cable
	    Diameter Ratio (d/D)
	Pitch to Cable Diameter Ratio (P/D)
	Percent Coverage
	Reversing Helix
	No. of Ridges

Table 2. Structural and Fluid Dynamic Parameters

Notation	Parametric Definition
f	fundamental frequency of structure in test fluid
f_s	Strouhal shedding frequency
U	free stream flow velocity
ξ	angle between cable axis and flow (90° is cable axis normal to flow)
M	virtual mass (mass plus added mass)
D	diameter of cylinder or cable
δ	logarithmic decrement
ρ	density of test fluid
C_D	drag coefficient
C_L	lift coefficient
Am_1	vibration amplitude with suppression device
Am	vibration amplitude without suppression device
A_{c1}	acceleration with suppression device
Ac	accleration without suppression device
P	pitch of helical spiral of device on cable
d	diameter of ridge
C_t	tangential drag coefficient

Table 3. Cable Drag and Vibration [4]

Fairing	Description	C_D at $Re=1.2 \times 10^5$	Speed of the Flow	Vibration Amplitude
Wire rope	Bare	1.4	Vibration at all speeds	
Thonged rope	4 in. (102 mm) long, 4/in.	1.3	5-10 knots[a] 10-15 knots[b]	Negligible Reduced
	8 in. (204 mm) long, 4/in.	1.5	5-10 knots 10-15 knots	Negligible Reduced
	8 in. (204 mm) long, 6/in.	2.6	5-10 knots 10-15 knots	Negligible Reduced
	With overhand knot, 4/in.	1.5	5-10 knots other speeds	Negligible Same

[a] 2.6 - 5.2 m/s.
[b] 5.2 - 7.7 m/s.

Table 4. Parameters for G.E.'s Faired Cable Tests [8]

Acceleration readings taken at midpoint, quarter point, and one-third point; tangential, normal, and lift forces obtained from triaxial force gage.

Geometry	Parameters
Helix wrap	
Material	Polypropylene
Length	7 in. (120 mm)
Spacing	7/8 in. (22 mm)
P/D	10
	Fringe applied to 0.25-in. (0.006 m) cable spiraled around a 0.70-in. (0.018 m) cable
Trailing	
Material	Polypropylene and polyester monofilament
Length	4.5 in. (110 mm)
Spacing	7/8 in. (22 mm)
	Fringe applied to 0.81-in. (21 mm) cable

Table 5. Summary of Parameters for Various Strum Suppressed Cables

Run No.	Model	Angle (Deg)	Static Tension (lb)	Symbol[a]
4	Bare cable	90	45	
1				
3				⊘
5				
6				
8			138	
9			134	
11			136	○
14			133	
12				
13				
16				
17			212	◒
18				
24	Bare cable with helical wrap of fringe fairing	90	62	□
25			63	
26				
29		90	136	
30				⬓
31				
28				
32				
33				
20		90	235	
21			234	◪
22				
35	Bare cable with helical wrap of fringe fairing	90	138	
36				◇
37				
38				
45	Bare cable with helical wrap of fringe fairing cut back to one-third length fringe	90	136	
46				△
47				
48				

[a]These symbols are used in Figures 8 and 9.

Table 5. (Continued)

Run No.	Model	Angle (Deg)	Static Tension (lb)	Symbol
40 41 42 43	Bare Cable with helical wrap of fringe fairing with one-third tufts removed	90	136	◺
50 51 52 53	Bare cable with helical wrap of fringe fairing with two-thirds tufts removed	90	134 133 134	⌓
64 65 66 67	Bare Cable	60	106	⊗
68 69 70 71	Bare cable with helical wrap of fringe fairing cut back to one-third length fairing	60	99	▲
72 73 74 75	Bare cable with helical wrap of fringe fairing with two-thirds tufts removed	60	99	●

Table 6. Summary of Cable Strumming Data for MIT Experiments (from Reference 10)

Cable Description	Sampson Blue Streak	Wire Rope	Phyllistran	Antistrumming Kevlar w/w.o. Fairing[a]
Measured diameter in inches (mm) under tension	0.39 (9.9)	0.275 (7.0)	0.485 (12.3)	0.154 (3.9)
Linear density in air, lb/ft (N/m)	0.044 (0.64)	0.073 (1.1)	0.076 (1.1)	0.011/.010 (0.16/0.15)
Construction	12-strand single braid, polyester and polypropylene	3 x 9 torque balanced galvanized plow steel	7 x 7 "Kevlar" with polyurethane jacket	Braided polyurethane impregnated Kevlar, with three twisted conductors down center
Breaking strength, lb (N)	5,000 (22,240)	4,000 (17,792)	17,000 (75,616)	2,000 (8,896)
Current range, ft/sec (m/s)	0.26 - 2.1 (0.08 - 0.64)	0.2 - 2.4 (0.06 - 0.73)	0.25 - 2.2 (0.08 - 0.67)	1.6 - 2.1 (0.49 - 0.64)
Reynolds no. range	660 - 5200	360 - 4200	800 - 6850	1500 - 2100
Frequency range (Hz)	1.3 - 11.3	2.2 - 18.3	1.5 - 12.1	14.3 - 21.3/[illegible] - 27.8
Strouhal no. range	0.16 - 0.18	0.16 - 0.18	0.20 - 0.22	0.12 - 0.13[b]/0.17
Tension range, lb (N)	70 - 230 (311 - 1023 N)	60 - 580 (267 - 2580 N)	110 - 450 (489 - 2001 N)	65 - 80 (289 - 356 N)
Typical amplitude (diam)	0.4 - 0.7	0.4 - 0.7	0.3 - 0.5	0.5[b]/0.5 - 0.7

[a]Fairing: 1/16" synthetic fuzz woven helically into Kevlar braid.
[b]Based on unfaired diameter.

Table 7. Standard Configuration for DTNSRDC Ribbon Fairing

[Cable is bare and tension is 1,200 lb (5,338N) in all cases.]

Cable Diameter, in. (mm)	Angle of Inclination, deg	Flow Velocity, knots (m/s)	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, c^2 s
0.35 (8.9)	90	6 (11.2)	70.0	140.0
			73.0	106.0
			68.0	123.0
			70.0	132.0
			68.0	130.0
			68.0	133.0
0.35 (8.9)	45	6 (11.2)	48.0	40.7
0.5 (12.7)	90	6 (11.2)	54.0	62.2
0.5 (12.7)	45	6 (11.2)	32.0	43.3

Table 8. Speed Variations
For DTNSRDC Ribbon Fairing

[Tension is 1,200 lb (5,338N) in all cases.]

Cable Diameter, in. (mm)	Angle of Inclination, deg	Flow Velocity, knots (m/s)	Ribbon	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35 (8.9)	90	2 (3.7)	Bare	75.0	4
		4 (7.4)	Bare	41.7	9
		5 (9.3)	Bare	58.0	31
		6 (11.2)	Bare	73.0	100
0.35 (8.9)	45	2 (3.7)	Bare	56.0	8
		4 (7.4)	Bare	34.0	54
		5 (9.3)	Bare	41.8	77
		6 (11.2)	Bare	48.0	100
0.35 (8.9)	90	2 (3.7)	4x2x2	28.3	0
		4 (7.4)	4x2x2	30.8	5
		5 (9.3)	4x2x2	54.1	7
		6 (11.2)	4x2x2	54.0	38
0.5 (12.7)	90	2 (3.7)	Bare	15.0	2
		4 (7.4)	Bare	32.2	32
		5 (9.3)	Bare	37.8	53
		6 (11.2)	Bare	54.0	100
0.5 (12.7)	45	2 (3.7)	Bare	26.3	5
		4 (7.4)	Bare	25.4	76
		5 (9.3)	Bare	27.4	76
		6 (11.2)	Bare	34.7	100
0.5 (12.7)	90	2 (3.7)	10x1x0	28.5	0
		4 (7.4)	10x1x0	25.5	1
		5 (9.3)	10x1x0	25.9	3
		6 (11.2)	10x1x0	35.8	14

Table 9. Angle Variations
For DTNSRDC Ribbon Fairing

[Cable is bare and tension is 1,200 lb (5,338N) in all cases].

Cable Diameter, inches (mm)	Angle of Inclination, deg	Flow Velocity, knots (m/s)	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, G^2 s
0.35 (8.9)	90	6 (11.2)	69.5	127.0
	60		55.0	101.0
	45		48.0	40.7
	30		31.0	30.5

Table 10. Tension Variations For DTNSRDC Ribbon Fairing

Cable Diameter, inches (mm)	Angle of Inclination degrees	Flow Velocity, knots (m/s)	Tension, lb (N)	Ribbon	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35	90	6	800 (3558)	Bare	66.0	78
(8.9)		(11.2)	1000 (4448)	Bare	66.0	87
			1200 (5338)	Bare	73.0	100
			1400 (6227)	Bare	74.0	55
0.35	45	6	800 (3558)	Bare	45.0	141
(8.9)		(11.2)	1000 (4448)	Bare	48.0	57
			1200 (5338)	Bare	48.0	100
			1400 (6227)	Bare	44.5	87
			1600 (7117)	Bare	47.0	108
0.5	45	6	800 (3558)	Bare	34.7	147
(12.7)		(11.2)	1200 (5338)	Bare	39.9	100
			1600 (7117)	Bare	36.4	145
0.35	90	6	800 (3558)	10x1x0	49.0	10
(8.9)		(11.2)	1200 (5338)	10x1x0	49.5	24
			1600 (7117)	10x1x0	51.0	14

Table 11. Ribbon Length Variations For DTNSRDC Ribbon Fairing

[Tension is 1,200 lb (5,338N) in all cases.]

Cable Diameter, inches (mm)	Angle of Inclination, deg	Flow Velocity, knots (m/s)	Ribbon	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35 (8.9)	90	6 (11.2)	10x1x0	47.0	24
			8x1x0	49.5	14
			6x1x0	54.0	11
			4x1x0	53.0	18
			10x1x1	60.0	5
			8x1x1	57.0	28
			6x1x1	58.0	11
			4x1x1	56.0	7
0.35 (8.9)	45	6 (11.2)	10x1x0	33.0	46
			8x1x0	31.4	37
			6x1x0	32.3	45
			4x1x0	34.3	33
			10x1x1	29.0	45
			8x1x1	40.5	54
			6x1x1	44.0	46
			4x1x1	42.5	88
0.35 (8.9)	90	6 (11.2)	10x2x0	40.0	7
			7x2x0	44.7	4
			4x2x0	47.8	15
			10x2x1	47.8	15
			7x2x1	50.5	1
			4x2x1	50.8	12

Table 11. Ribbon Length Variations For DTNSRDC Ribbon Fairing (From Reference 14) (Continued)

[Flow velocity is 6 knots (11.2 m/s) and tension is 1,2000 lb (5,338 N) in all cases.]

Cable Diameter, inches (mm)	Angle of Inclination, deg	Ribbon	Frequency of Transverse Acceleration, Hz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35 (8.9)	45	10x2x0	24.0	1
		7x2x0	27.8	1
		4x2x0	34.2	6
		10x2x1	28.3	1
		7x2x1	30.2	1
		4x2x1	34.0	9
0.5 (12.7)	90	10x1x0	40.0	3
		8x1x0	36.5	18
		6x1x0	40.5	28
		4x1x0	40.2	9
0.5 (12.7)	45	10x1x0	28.4	0
		8x1x0	27.8	2
		6x1x0	28.7	2
		4x4x0	27.1	2

Table 12. Ribbon Spacing Variations for DTNJRDC Ribbon Fairing (from Reference 14)

[Flow velocity is 6 knots (11.2 m/s) and tension is 1,200 lb (5,338 N) in all cases.]

Cable Diameter, inches (mm)	Angle of Inclination, degrees	Ribbon	Frequency of Transverse Acceleration, hertz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35 (8.9)	90	10x1x0	47.0	24
		10x1x½	53.0	9
		10x1x1	60.0	5
		10x1x2	56.0	6
		10x1x3	66.0	55
		10x1x5	66.0	41
0.35	45	10x1x0	33.0	46
		10x1x½	34.2	42
		10x1x1	29.0	45
		10x1x2	42.2	52
		10x1x3	43.0	120
		10x1x5	48.0	97
0.5 (12.7)	90	10x1x0	40.0	3
		10x1x½	36.5	10
		10x1x1	36.0	9
		10x1x2	49.8	33
0.5 (12.7)	45	10x1x0	28.4	0
		10x1x½	29.5	3
		10x1x1	31.9	11
		10x1x2	33.0	65
0.35 (8.9)	90	4x2x0	47.8	5
		4x2x1	50.1	13
		4x2x2	54.0	36
		4x2x4	56.0	21

Table 12. Ribbon Spacing Variations for DTNSRDC Ribbon Fairing (from Reference 14) (Continued)

[Flow velocity is 6 knots (11.2 m/s) and tension is 1,200 lb (5,338 N) in all cases.]

Cable Diameter, inches (mm)	Angle of Inclination, degrees	Ribbon	Frequency of Transverse Acceleration, Hertz	Peak in Power Spectrum of Transverse Acceleration, % of Bare Cable Value
0.35 (8.9)	45	4x2x0	34.2	6
		4x2x1	34.0	18
		4x2x2	35.3	10
		4x2x4	37.0	15

Table 13. Ribbon Fairing Characteristics

Configuration		Flow	Remarks
Width, in. (mm)	Length, in. (mm)		
½ (12.7)	3 (76.2)	accelerated uniformly to 5 knots and decelerated to 0 knots	100% coverage
½ (12.7)	3 (76.2)		50% coverage
½ (12.7)	2 (50.8)		100% coverage
1 (25.4)	3 (76.2)		Ribbons spaced 1 diameter apart
1 (25.4)	3 (76.2)		ribbons spaced 2 diameters apart

Table 14. NUC Model Characteristics [12]

Model	Type	Configuration
M12	Zip-On	Continuous flag of vinyl-impregnated nylon cloth; 20 in. (508 mm) chord x 0.019 in. (0.98 mm) thick; ends cut at 20 deg angle.
M12A	Zip-On	Same as M12 but 12 in. (305 mm) chord cut at y = 15 deg, h = 48 in. (1219 mm)
M12B	Zip-On	Same as M12A except h = 24 in. (610 mm)
M12C	Zip-On	Same as M12A except h = 12 in. (305 mm)
M12D	Zip-On	Same as M12A except h = 6 in. (152 mm)
M12E	Zip-On	Same as M12 except cut into narrow ribbons with y = 15 deg and width = 3/8 in. (9.5 mm).
M12F	Zip-On	Same as M12E except 6 in. (152 mm) cut off from ribbons.
M15	Ribbon	19 pairs 12 in. (305 mm) apart; each ribbon 7 in. (178 mm) long x 2 in. (50.8 mm) wide x 0.022 in. (0.56 mm) thick; material, double layer of adhesive tape; Ribbon angle = 45 deg.
M15A	Ribbon	Same as M15 except 38 pairs at 6 in. (0.152 mm) apart and ribbon angle = 90 deg.

Table 14. (Continued)

Model	Type	Configuration
M15B	Ribbon	Same as M15A with every other ribbon removed.
M24	Helical Ribbon	Helically wrapped ribbon 0.015 in. (0.397 mm) Ribbon angle = 30 deg, ribbon length = 10 in. (254 mm)
M25H	Helical Ribbon	Same as M24 but ribbon length = 13 in. (330 mm), ribbon angle - 15 deg
M29H	Helical Ribbon	Same as M24 but ribbon length = 12 in (305 mm), ribbon angle = 90 deg

Table 15. NUC Data for Ribbon Fairing [12][a]

Model	Re = 54.583						Re = 90.972						Re = 127,361					
	β (db)			C_D			β (db)			C_D			β (db)			C_D		
	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°
M12A					0.9	0.9					0.7	0.8					0.7	0.7
M12B			-27		1.2	0.9			-27		0.7	0.7			-22		0.8	0.8
M12C					1.2	1					0.8	0.8					0.8	0.8
M12D						0.9						0.75						0.85
M12E			-45			0.7			-27			0.75			-5			0.85
M12F						0.7						0.75						0.85
M15			-31			1.3			-28			1.2			-20			1.1
M15A						1						0.9						0.8
M15B						1.1						1						0.7
M24				4.1	1.4	1.4				2.1	1	1				2.5	0.9	0.9
M25H					1.2	1.2					1	1					1	0.8
M29H	2	-38	-47	8	2	1.4	-13	-30	-32	5.5	1.6	1.2	-30	-42	-37	4.5	1.6	1
Bare wire C_D				3.5	2.5	3.0				1.7	1.9	2.0				1.3	1.8	1.3

[a]Blanks indicate not tested.

Table 16. Summary of Model Characteristics (From Reference 28)

[Surface was smooth on all models except Model 10; helix reversal on all except Model 15.]

Model	Ridge Type	Pitch Ratio, P/D	Number of Ridges
1	1	20	1
2	2	20	1
3	3	20	1
4	4	20	1
5	5	20	1
6	6	20	1
7	7	20	1
8	8	20	1
11	1	40	1
12*	3	40	1
13*	6	40	1
14*	7	40	1
15	1	20	1
16	1	10	1
17*	3	10	1
18*	1	20	2
19	1	20	3
20	9	20	1
21	1	5	1
22	1	15	1
23	4	10	1
24	4	40	1
25	(Plastic Film Fairing		
26	(Splitter Plate Fairing)		

*Not tested

Table 17. Summary of Ridge Cross-Section Parameters (From Reference 28)[a]

Type	ridge height	ridge width	d	ridge width/D	ridge height/D	d/D
1	----	0.22	0.20	1.1	0.153	0.153
2	0.15	0.28	----	1.9	0.114	-----
3	0.22	0.40	----	1.8	0.168	-----
4	----	----	0.34	---	-----	0.260
5	0.23	0.23	----	1.0	0.176	-----
6	0.12	0.25	----	2.1	0.092	-----
7	0.12	0.50	----	4.2	0.092	-----
8	0.23	0.52	----	2.3	0.176	-----
9	----	----	0.15	---	-----	0.114

[a]Blanks indicate that it is not applicable

Table 18. Model Characteristics (NUC)

Model	Type	Configuration
M4	--	0.34 in.-(8.64 mm) diameter plastic wire, pitch/pipe diam. = 10, base fillet at junction of wire and pipe.
M4A	Helical	Same as M4 without fillet.
M4C	Ridge	Same as M4 with tape wraps at 13.1 in. (0.33 M) intervals.
M10	--	Single 0.5 inch (12.7 mm) wide by 0.25 in. (6.35 mm) high rectangular cross section; pitch/pipe diam. = 14, base fillet.

Table 19. NUC Helical Ridge

Model	Re = 54,583						Re = 90.972						Re = 127,361					
	β (db)			C_D			β (db)			C_D			β (db)			C_D		
	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°	5°	15°	25°
M4	5	-7	-30	4.8	2.8	2.2	-13	-20	-28	3.7	2.3	2.3	-21	-25	-25	3.4	2.2	0.9
M4A	2	-9	-28	–	–	–	-12	-18	-26	–	–	–	-20	-7	-12	–	–	–
M4C	-2	-31	-27	4.3	3.0	2.4	-16	-22	–	3.6	2.8	2.6	-18	-28	-18	3.5	2.8	1.0
M10	5	-27	-31	3.7	2.0	2.0	-5	-10	-26	3.0	2.0	2.0	-25	-16	-22	2.0	3.0	1.2

Table 20. Model Characteristics of Helical Ridges, DTNSRDC [15,16]

Wire Diameter/Cable diameter (d/D)	Pitch Length/Cable Diameter (P/D)
0.24	20
0.12	20
0.36	20
0.24	5
0.24	10
0.24	15
0.24	30
0.24	40

Table 21. G.E. Test Parameters

Re	Tension lb, (N)	Pitch/Cable Diameter	Wire Diameter/ Cable Diameter	Cable Axis to Flow, deg
3,217	61 (271.3)	10	0.25	90
4,817	138 (613.8)	10	0.25	90
6,435	246 (1094.3)	10	0.25	90

Table 22. Fringe Fairing Test Parameters

$[f/f_s = 1]$

Reference Number	Symbol[a]	Re Range	Angle Degrees	Material	Length in (mm)	Geometry	C_D	B, db (%)	Comments
8 Chey	F1	6435	90	Polypropylene	7 (178) 7/8 apart (2.2)	Helical P/D = 10 d/D = 0.31 D = 0.81	6.0	-38 (99)	Gives first through third harmonic wall rope works fringe
	F2	1094 N		Polyester monofilament	4.5 (114)	Longitudinal	scat-ter	-52 (100)	bare cable $0.7 < C_o < 1.9$
	F3			Polypropylene	4.5 (114)	Longitudinal	5.9	-38 (99)	Data taken at Strouhal velocity
	F15	4172	60	Polypropylene	7 (178) 7/8 apart (2.2)	Helical P/D = 10 d/D = 0.31	3.5	-54 (100)	
	F16	458 N		Polyester monofilament	4.5 (114)	Longitudinal	2.2	-52 (100)	
	F17			Polypropylene	4.5 (114)	Longitudinal	1.8	-46 (100)	
	F4	4817	90	Polypropylene	7 (178) 7/8 apart (2.2)	Helical P/D = 10 d/D = 0.31	--	-59 (100)	
	F5	614 N		Polyester monofilament	4.5 (114)	Longitudinal	3.5	-59 (100)	
	F6			Polypropylene	4.5 (114)	Longitudinal	2.0	-58 (100)	

[a]See Figures 37-41 for data points.

Table 22. (Continued)

$[f/f_s = 1]$

Peference Number	Symbol[a]	Re Range	Angle Degrees	Material	Length in. (mm)	Geometry	C_D	B, db (%)	Comments
8 Chey (Continued)	F7	3217	90	Polypropylene	7 (178) 7/8 apart (2.2)	Helical P/D = 10 d/D = 0.31	2.5	-18 (87)	
	F8	271N		Polyester monofilament	4.5 (114)	Longitudinal	0.5	-21 (91)	
	F9			Polypropylene	4.5 (114)	Longitudinal	1.6	-28 (96)	
7 Cohen	F10	$1.8 \times 10^3 - 5.4 \times 10^4$	90	Polyester yarn	5 1/2 (14) 1 apart (2.5)	Longitudinal	1.1	Amplitude bare 2.25 in. sup 0.75 in.	Wall Rope uniline cantelever rotated 360 degrees used only 0 degrees data at Strouhal Velocity; f = 26.5 Hz, Re = 3.3×10^4, V = 2.3m/s; See Figure 36 for C_D vs Re and C_D vs angle of rotation at V = 7.6 ft/s

[a]See Figures 37-41 for data points.

Table 22. (Continued)

$[f/f_s = 1]$

Reference Number	Symbol[a]	Re Range	Angle Degrees	Material	Length in. (mm)	Geometry	C_D	B, db (%)	Comments
4 Kelly & Goff	 F12 F13 F14	$1.4 \times 10^4 - 5.8 \times 10^4$ 1.2×10^5	small --	Nylon --	 4 (102) 8 (204) 8 (204)	Longitudinal 4/in. 4/in. 6/in.	 1.3 1.5 2.6	 -- -- --	Not really a fringe but rope thongs "towed" bare cable C_D = 1.4
6 Hayes, Nowak, Bou	 F18 F19 F20	$400 - 8.1 \times 10^3$ Resonance 1218	90	PVC	5 1/2 (140)	Longitudinal 1/2 in. spacing 1 in. spacing 2 in. spacing	-- -- -- --	 -26 (95) -26 (95) -12 (75)	Qualitative results
8 Chey Dec. Date G. E.									Acceleration data to be reduced See Table 5 and Figures 8 and 9
9 Kan	F21	1500-2100	90	Po./proplene yarn	--	--	--	--	Helical weave decreased amplitude 30%

[a]See Figures 37-41 for data points.

Table 23. Hair Fairing Test Parameters and Results

$[f/f_s = 1]$

Reference Number	Symbol[a]	Re Range	Angle Degrees	Material	Length in. (mm)	C_D	B, db (%)	Comments
11 Endeco (BRAINCON)	H2	10^5	Towed	Urethane rubber	11 (280)	0.4-0.6	-20 (90)	No data given for their C_D and acceleration reduction
12 Fabula and Bedore	H3	54,583	5	Urethane	11 (280)	--	-8 (60)	Endeco fairing natural frequency of system not given
	H4		10	Urethane	11 (280)	0.9	-44 (99)	
	H5		15	Urethane	11 (280)	0.9	-47 (100)	
	H6	90,972	5	Urethane	11 (280)	--	-18 (87)	
	H7		10	Urethane	11 (280)	0.7	-23 (93)	
	H8		15	Urethane	11 (280)	0.7	-33 (98)	
	H9	127,361	5	Urethane	11 (280)	--	-30 (97)	
	H10		10	Urethane	11 (280)	0.6	-37 (99)	
	H11		15	Urethane	11 (280)	0.5	-45 (99)	
6 Hays, Nowak, Boutin	H1	400-8100 1218 resonance	90	PVC	5 (127)	--	-25 (94)	Prodesco – helical
4 Kelly and Goff	H12	6.3×10^4	Towed	Urethane	11 (280)	1.3	--	BRAINCON hair
	H13	6.3×10^4	Towed	Urethane		1.7		Double hair
	H14	1.2×10^5	Towed	Cloth hair	4 (102)	2.2	--	
13 Dale, et. al.			90	Spiraled cotton thread				
	H15	600				1.8	--	
	H16	700				1.75	--	
	H17	900				1.53	--	
	H18	1150				1.1		

[a]See Figure 37 for C_D versus Re and C_D versus angle of rotation at V = 7.6 ft/s.

Table 24. Ribbon Fairing Test Parameters and Results

Length x Width x Spacing X x Y x Z

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Material	Geometry	C_D	B, db (%)	Comments
14 Blevins				Polyurethane 0.015 in. thick (0.38 mm)		--		Longitudinal attachment but spiraled under
	R1	22,750	90	D = 0.35 in. (8.9 mm)	4 x 2 x 2	--	(38)	tension. Acceleration expressed
		32,500	90	D = 0.5 in. (12.7 mm)	10 x 1 x 0	--	(14)	as percent of peak spectrum at
	R2	22,750	90		10 x 1 x 0	--	(24)	resonance.
	R3				8 x 1 x 0	--	(14)	Maximum vibration at R_e =
	R4				6 x 1 x 0	--	(11)	22,750
	R5				4 x 1 x 0	--	(18)	
	R6				10 x 1 x 1	--	(5)	
	R7				8 x 1 x 1	--	(28)	
	R8				6 x 1 x 1	--	(11)	
	R9				4 x 1 x 1	--	(7)	
	R25A		45		10 x 1 x 0	--	(46)	
	R26A				8 x 1 x 0	--	(37)	
	R27				6 x 1 x 0	--	(45)	
	R28				4 x 1 x 0	--	(33)	
	R29				10 x 1 x 1	--	(45)	
	R30				8 x 1 x 1	--	(54)	
	R31				6 x 1 x 1	--	(46)	
	R32				4 x 1 x 1	--	(88)	
	R10		90		10 x 2 x 0	--	(7)	
	R11				7 x 2 x 0	--	(4)	
	R12				4 x 2 x 0	--	(15)	
	R13				10 x 2 x 1	--	(15)	
	R14				7 x 2 x 1	--	(1)	
	R15				4 x 2 x 1	--	(12)	
	R33		45		10 x 2 x 0	--	(1)	
	R34				7 x 2 x 0	--	(1)	
	R35				4 x 2 x 0	--	(6)	
	R36				10 x 2 x 1	--	(1)	
	R37				7 x 2 x 1	--	(1)	

Table 24. (Continued)

Length x Width x Spacing X x Y x Z

[$f/f_s = 1$]

Reference Number	Symbol	Re Range	Angle Degrees	Material	Geometry	C_D	B, db (%)	Comments
14 (Continued)	R38	22,750	45		4 x 2 x 1	--	(9)	
		32,500	90		10 x 1 x 0	--	(3)	
					8 x 1 x 0	--	(18)	
					6 x 1 x 0	--	(28)	
					4 x 1 x 0	--	(9)	
			45		10 x 1 x 0	--	(0)	
					8 x 1 x 0	--	(2)	
					6 x 1 x 0	--	(2)	
					4 x 1 x 0	--	(2)	
	R16	22,750	90		10 x 1 x ½	--	(9)	
	R17				10 x 1 x 2	--	(6)	
	R18				10 x 1 x 3	--	(55)	
	R19				10 x 1 x 5	--	(41)	
	R39		45		10 x 1 x ½	--	(42)	
	R40				10 x 1 x 2	--	(52)	
	R41				10 x 1 x 3	--	(120)	
	R42				10 x 1 x 5	--	(97)	
	R43				4 x 2 x 2	--	(10)	
	R44				4 x 2 x 4	--	(15)	
	R20		90		4 x 2 x 2	--	(36)	
	R21				4 x 2 x 4	--	(21)	
	R22	32,500			10 x 1 x ½	--	(10)	
	R23				10 x 1 x 1	--	(9)	
	R24				10 x 1 x 2	--	(33)	
	R45		45		10 x 1 x ½	--	(3)	
	R46				10 x 1 x 1	--	(11)	
	R47				10 x 1 x 2	--	(65)	
16 Doolittle	R48	17.160	15	--	6 x 1 x 1	--	-23 (93)	Tests were run at 2, 3 and 5 knots (3.7, 5.3, 9.2 m/sec) but only 3 knots (5.3 m/sec) is presented since bare cable resonated at that speed up to sixth hamonic presented.
	R49	d = 0.528 in.			6 x 1 x 0	--	-27 (96)	
	R50				6 x 1 x ½	--	-25 (94)	
	R51				6 x 1 x 2	--	-23 (93)	
	R52				4 x 1 x 0	--	-28 (96)	
	R53				4 x 1 x ½	--	-27 (96)	

Table 24. (Continued)

Length x Width x Spacing X x Y x Z

$[f/s_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Material	Geometry	C_Γ	B, db (%)	Comments
16 (Continued)	R54		15		4 x 1 x 1	--	-26 (95)	
	R55				4 x 1 x 2	--	-23 (93)	
	R56				6 x 2 x 1	--	-27 (96)	
	R57				6 x 2 x 2	--	-24 (94)	
	R58				6 x 1 x 4	--	-8 (60)	
	R59				6 x 2 x 4	--	-11 (72)	
	R60				4 x 1 x 4	--	-6 (50)	
	R61			Stubs	6 x 1 x ½	--	-37 (99)	Stubs were in the spacing between full ribbons
	R62				6 x 1 x 1	--	-9 (65)	
	R63				6 x 1 x 2	--	-3 (29)	
15 Diggs		$6 \times 10^4 - 2.5 \times 10^5$	Towed 15	Folyurethane 15 and 30 mil				d = 0.84 in. (21.3mm) tests conducted at sea speeds 6, 9, 12, 15 knots (11.2, 16.6, 21.2, 27.9 m/s)
	R64	7×10^4		15 mil	6 x 2 x 2	1.2		
	R65			30 mil	6 x 2 x 2	3.4		
	R66			25% stubs	6 x 2 x 4	2.3		
	R67			37½% stubs	6 x 2 x 8	1.9		
	R68			50% Stubs	-----	1.6		
	R69	1.6×10^5		15	6 x 2 x 2	1.7		
	R70			30	6 x 2 x 2	4.5		
	R71			25%	6 x 2 x 4	3.4		
	R72			37½%	6 x 2 x 8	4.6		
	R73			50%	-----	4.4		
	R74	2×10^5		15	6 x 2 x 2	2.3		
	R75			30	6 x 2 x 2	6.0		
	R76			25%	6 x 2 x 4	5.0		
	R77			37½%	6 x 2 x 8	8.1		
	R78			50%	-----	8.2		

Table 24. (Continued)

Length x Width x Spacing   X x Y x Z

[$f/f_s = 1$]

Reference Number	Symbol	Re Range	Angle Degrees	Material	Geometry	C_D	B, db (%)	Comments
12 Fabula and Bedore	R79	$5.4 \times 10^4 - 1.3 \times 10^5$	5, 10, 15	PVC	4½ x ½ x 0	See Table 14		Zip-on ribbon
6 Hays, Nowak, Boutin		800-3600	90	Polyurethane 6 mil	4 in. long spiraled	--		
	R25	1218					-22 (92)	
	R26	1218			5 x 2 x ½	--	-27 (96)	
		1625			4½ x ½ x 0	--	-33 (98)	

Table 25. *Helical Ridge Test Parameters and Results (Also Longitudinal)*

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
8 Chey Low Strumming	S1	3217 (271N)	90	Round	1	10	0.25	0.4-2.3	-5 (44)	First through third harmonic given
	S2	4817 (614N)	90	Round	1	10	0.25	0.2	-11 (72)	
	S3	6435 (1094N)	90	Round	1	10	0.25	1.2-0.9	-25 (94)	
18 Cowdrey and Lawes		$8.5 \times 10^4 - 3.8 \times 10^6$	90	Rectangular	3	11.3				Rigid cylinder gives curve of C_D based on circumscribed cylinder compound to bare cylinder
	S21	8.5×10^4					0.059	1.23		
	S22	3×10^5						1.25		
	S23	6.3×10^5						1.27		
	S24	1.8×10^6						1.30		
	S25	2.6×10^6						1.29		
	S26	3.8×10^6						1.27		
	S27	8.5×10^4					0.118	1.38		
	S28	3×10^5						1.40		
	S29	6.3×10^5						1.42		
	S30	1.8×10^6						1.45		
	S31	2.6×10^6						1.44		
	S32	3.8×10^6						1.42		
13 Dale, McCandless and Holler			90	Twisted pair	–	15	d = 0.057 in.			
	S4	650						0.95		
	S5	850						0.90		
	S6	1200						0.85		
15 Diggs	S7	6.1×10^4	Towed <15	Round	1	15	0.23	1.5		Helix reversal every 10 feet (3.05m) bare $C_D = 2.0$
	S8					15		1.7		
	S9				at sea	20		1.2		
	S10					30		1.5		
	S11	10^5				15		1.9		
	S12					15		1.5		
	S13				at sea	20		1.1		
	S14					30		1.2		

Table 25. (Continued)

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
15 (Continued)	S15	1.3×10^5	Towed <15	Round	at sea	15		1.5		
	S16					20		1.4		
	S17					30		1.4		
	S18	1.7×10^5			at sea	15		1.8		
	S19					20		1.8		
	S20					30		1.7		
26 Joubert and Hoffman	S33	6.4×10^4	90	Rectangular longitudinal at 50 degrees from front stagnation	2	--	1.2 time boundary layer height	0.57		Rigid cylinder
	S34	9.5×10^4						0.51		
	S35	1.3×10^5						0.42		
	S36	1.6×10^5						0.38		
	S37	1.8×10^5	90					0.38		
	S38	3×10^5						1.02		
	S39	3.5×10^5						1.15		
	S40	4×10^5						1.15		
	S41	5×10^5						1.15		
	S42	5.7×10^5						1.18		
16 Doolittle	S43	17,160	15	Round	1	10	0.24		-17 (86)	Reverse helix at midspan
	S44					10	0.36		-14 (80)	
	S45					15	0.12		-8 (60)	
	S46					15	0.24		-24 (94)	
	S47					15	0.36		-22 (92)	
	S48					20	0.12		-9 (65)	
	S49					20	0.24		-15 (82)	
	S50					20	0.36		-17 (86)	
	S51					30	0.24		-8 (60)	
	S52					30	0.36		-11 (72)	
	S53					40	0.24		-7 (55)	
	S54					40	0.36		-7 (55)	

Table 25. (Continued)

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
28 Fabula and Bedore	S55	50,000	20	Rounded	1	20	0.114		0.67 in. (26)	Helix reversal at midpoint
	S56	Resonance					0.153		0.55 in. (39)	
	S57	↓					0.260		0.12 in. (87)	Width/Height
	S58			Rectangular	1	20	0.092		0.45 in. (50)	2.1 Used accel.
	S59						0.092		0.5 in. (44)	4.2 trace ampl. in
	S60						0.176		0.15 in. (83)	1.0 inches smooth
	S61						0.176		0.05 in. (94)	2.3 −0.9 in.
	S62			Round	1	10	0.26		0.05 in. (94)	
	S63					20	0.26		0.07 in. (92)	
	S64					40	0.26		0.21 in. (77)	
	S65					5	0.153		0.08 in. (91)	25% removal from mid-
	S66					10	0.153		0.08 in. (91)	point of
	S67					15	0.153		0.05 in. (94)	did not affect results
	S68					20	0.153		0.6 in. (93)	
	S69	↓				40	0.153		0.6 in. (93)	

Table 25. (Continued)

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
28 (Continued)	S70	Resonance		Round	3	20	0.153		0.48 in. (47)	
	S71				1	20	0.153		0.5 in. (94)	⇐ No helix reversal
12 Fabula and Bedore	S72	54,500	5	Round	1	10	0.26	4.8	+5 (44)	Also see Table 19.
	S73		15					2.8	-7 (55)	
	S74		25					2.2	-30 (97)	
	S75	100,000	5					3.7	-13 (78)	
	S76		15					2.3	-19 (89)	
	S77		25					2.3	-27 (96)	
	S78	127,000	5					3.4	-22 (92)	
	S79		15					2.2	-26 (95)	
	S80		25					0.9	-25 (94)	
17 Price		4640	90	Round	2 (long)			--		60 degrees from flow no beneficial suppression of vibration
				3 parallel			0.023			
				3 helical	2		0.023			
				6 helical	.5		0.023			
					4					
					8					
					16					
					20					
					.8		0.026			
					1		0.029			
					20		0.032			
19 Scruton and Walshe		Not given	90	3 helical rectangular	3	15	0.059		0.17 Diam.	Varied structural damping $2M\delta/eD^2$ 0.17 maximum for smooth cylinder
							0.088		0.17 Diam.	
							0.118		0.12 Diam. (0)	

Table 25. (Continued)

$[f/f_s = 1]$

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
20 Scruton		70 ft/s	90	3 helical rectangular	3	5	0.10		reduced ampl. 99% from 9.5 in.	No diameter given used wind speed (Reference 19 and 24)
22 Walshe	S81 S82 S83 S84 S85 S86 S87	12,100 12,300 15,600 19,600 22,300 46,600	90-55 45-50 40 35 30 25 20	3 helical rectangular	3	2	0.125		0.18 in. (76)	Smooth cylinder A = 0.76 in.
23 Walshe and Cowdrey		Not given	90	Rectangular Strakes on upper one-third of cylinder	3			δ_s = .01 δ_s = .02	0.18 in. 0.06 in.	Smooth cylinder ampl. ⇒ 0.06 in. $a\delta$ = 0.02 0.18 in. at a = 0.01
25 Weaver		$10^4 - 10^5$	90	Tubular	4	12	0.08			Results as coefficient of fluctuating lift
24 Woodgate and		Not given	90	Rectangular	3 6 1 2 3 6	7 7 4.8	0.059 0.059		0.24 in. 0.24 in. 0.22 in. 0.23 in. 0.23 in. –	

Table 25. (Continued)

[$f/f_s = 1$]

Reference Number	Symbol	Re Range	Angle Degrees	Geometry	No. of Ridges	P/D	d/D	C_D	B, db (%)	Comments
24 (Continued)					3	15	0.088		0.53 in.	
					2	7			––	
					3	7			0.23 in.	
					2	4.8			––	
					3	4.8			0.20 in.	
					2	3.6			––	
					3	3.6			0.22 in.	
					2	2.4			0.22 in.	
					1	7	0.118		––	
					2	7			––	
					3	7			0.20 in.	
					1	4.8			0.30 in.	
					2	4.8			––	
					3	4.8			––	
					6	4.8				

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